

I. A PALEOMAGNETIC APPROACH TO THE PRECAMBRIAN - CAMBRIAN
BOUNDARY PROBLEM

II. BIOGENIC MAGNETITE: ITS ROLE IN THE MAGNETIZATION OF
SEDIMENTS AND AS THE BASIS OF MAGNETIC FIELD
DETECTION IN ANIMALS

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A Dissertation
Presented to the
Faculty of Princeton University
In Candidacy for the Degree
of Doctor of Philosophy

Recommended for acceptance by the
Department of

Geological and Geophysical Sciences

May, 1979



To be successful in unlocking the doors concealing nature's secrets, a person must have ingenuity. If he does not have the key for the lock, he must not hesitate to try to pick it, to climb in a window, or even to kick in a panel.

(Hildebrand 1957)

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ACKNOWLEDGEMENTS

It is with great pleasure that I acknowledge the many people and organizations who contributed to and made this work possible. Formost among those is Prof. Heinz Lowenstam, who first stimulated my interest both in the Precambrian - Cambrian boundary problem and in the biomineralization of magnetite. Prof. E. M. Shoemaker I thank for diverting me from biology towards geophysics, and for the use of a superconducting rock magnetometer without which the Australian work could not have been done. My advisors at Princeton, A.G. Fischer, R.B. Hargraves, and K.S. Deffeyes are largely responsible for the subsequent evolution of my work; their help and friendly encouragement was absolutely necessary for sanity. M.E. Purucker, D.P. Elston, C.T. Klootwijk, B.J.J. Embleton, M.A. Vincent, G. Choubert, A. Yu. Rozanov, and T.P. Fletcher all aided in one way or another my sample collection and field work. Dr. M.W. McElhinny and the Research School of Earth Sciences of the Australian National University generously made their laboratory facilities and field vehicles available. Support for this work came from the Thomas J. Watson Foundation, the U.S. Geological Survey in Flagstaff, Arizona, the National Science Foundation, the National Academy of Sciences, the Moroccan B.R.P.M., and the Palaeontologic Institute of the U.S.S.R.

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I. A PALEOMAGNETIC APPROACH TO THE PRECAMBRIAN - CAMBRIAN BOUNDARY PROBLEM. II. BIOGENIC MAGNETITE: ITS ROLE IN THE MAGNETIZATION OF SEDIMENTS AND AS THE BASIS OF MAGNETIC FIELD DETECTION IN ANIMALS.

Abstract

I. New paleomagnetic results are reported from late Precambrian and lower Cambrian sediments in Central and South Australia, Morocco, the Siberian Platform, and Eastern Newfoundland. The magnetic polarity history recorded in the primary magnetization from these units starts with a mixed interval in the late Precambrian, followed by a long reversed, a long normal, and finally by mixed polarities in the Lower Cambrian. Comparison of magnetic polarity patterns from within the Lower Cambrian of the Siberian platform and Australia suggest that strata of upper Tommotian and lower Atdabanian age are not preserved in the Amadeus Basin. A pole position from the base of the Série lie de vin in the Anti-Atlas Mountains, Morocco lies on the African apparent polar wander path, indicating an Upper Riphean age. Early Cambrian claystone and limestone on the Burin Peninsula, Eastern Newfoundland were remagnetized probably during early-mid Ordovician time; this remagnetized direction suggests that Eastern Newfoundland was then moving with the British Isles. It is suggested that the Precambrian - Cambrian boundary be located at a geomagnetic transition.

Application of principal component analysis to demagnetization data in paleomagnetic studies provides one least-squares technique which can replace vector subtraction, remagnetization circles, and difference vectors; it further provides a better method for calculating Hoffman-Day

directions. Two new techniques are developed based on least-squares minimization and Bingham statistics for estimating a remanence direction using both demagnetization lines and planes. Finally, a method is developed for estimating the direction of a secondary component which is independent of structural correction in a tectonically folded area. Computer programs which perform these procedures are appended.

II. Organic magnetite formed by chitons and bacteria may be responsible for much of the stable magnetic remanence in marine and freshwater sedimentary rocks. Magnetite in chitons is always formed through the metabolic conversion of the mineral ferrihydrite, enabling them to wear away and replace about 1 magnetite tooth per day, shedding small fragments into the ocean. The grain size in most species examined is near $0.1 \mu\text{m}$, and falls within the single-domain (SD) stability field for magnetite. Both bacteria and chitons may have been contributing SD magnetite to sediments throughout a large portion of Geologic time.

Similar biogenic magnetite was found both in honey bees and pigeons, and delocalized remanence, again probably due to magnetite, measured in shark embryos. The known phyletic range of magnetite biosynthesis now extends from bacteria through vertebrates. Behavioral experiments in honey bees indicate that superparamagnetic (SPM) as well as perhaps SD magnetite grains are involved in the detection process; over 10^8 SPM grains between 300 and 350 Å in diameter are present in honey bees, while pigeons have between 10^7 and 10^8 SD grains. Four basic ferrimagnetic models for magnetic field detection in animals are discussed, several of which allow magnetic intensity resolution on the order of $5 \times 10^{-9} \text{ T}$ (5γ), well within the range of diurnal variations. In particular, one of the

SPM models totally accounts for the honey bee waggle dance orientation, and leads to specific, testable predictions about the configuration of their magnetoreceptor. The magnetic remanence in sharks is associated in part with the lateral line, suggesting that their prime magnetic sense is ferrimagnetic. If so, they could estimate the strength of self-induced electric fields, subtract it from measured fields, and find the electric component attributable to prey. Organic magnetite is likely to be the basis for magnetic field reception in animals.

The Precambrian - Cambrian Boundary Problem: A Proposed Solution.

Introduction to Part I of PhD Thesis,
Princeton University, Princeton, N.J.

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Geophysical Sciences.

INTRODUCTION

All research in the Earth Sciences depends upon the ability to sequence and compare things that happen in geologic time. Throughout most of the Phanerozoic, an age relationship between two events at separate localities is usually found by connecting them to biostratigraphic, paleomagnetic, or chronostratigraphic (radiometric) time scales. Events dated with one of these scales may be reasonably compared to those dated with another for rocks of the Devonian system and younger, but it is practically impossible to cross-correlate them in the Precambrian, Cambrian, and Ordovician. These poor correlations, however, are often used in many Late Precambrian and lower Paleozoic apparent polar wander tracks and continental reconstructions which are based on paleomagnetic data (Morel and Irving, 1978; McElhinny and McWilliams, 1977). Fossil magnetism is found equally well in sedimentary units which are most easily dated by paleontology and in igneous and metamorphic terrains that are commonly dated radiometrically. Ultimately, paleomagnetism may provide the connecting link between these time scales for this portion of the Phanerozoic. Paleomagnetic results presented and discussed here aim at refining biostratigraphic and lithostratigraphic correlations near the Precambrian - Cambrian transition, and should eventually provide a base for other geologic studies.

Correlation is also necessary for successful paleogeographic reconstructions based on paleomagnetic data. The absolute radiometric age of the magnetism involved is not essential, it is sufficient to know that the directions being compared are contemporaneous to within a

few million years. For the lower Cambrian, this degree of resolution at present is only possible with biostratigraphy (see, for example, Palmer 1977); radiometric and paleomagnetic time scales do not yet have the required level of precision. The Precambrian - Cambrian boundary working group (IGCP project #29) has spent several years locating unmetamorphosed Late Precambrian to lower Cambrian sequences which are useful for biostratigraphic correlation (Cowie and Glaessner 1975; Cowie 1978). To date, such sequences have been reported from Central and South Australia, Antarctica, Siberia, Mongolia, China, Morocco, Southwest Africa, Alberta, Baltica (Russian Platform), Newfoundland, Greenland, Spain, and California. It seems natural to use this stratigraphic work as a basis for paleomagnetic studies. The lower Cambrian is at the current limit of biostratigraphic resolution; in lieu of some unforeseen breakthrough in correlation, this may be as far back in time that we can realistically push paleogeographic reconstructions.

The philosophy underlying the start which I have made on this problem for the Late Precambrian and lower Cambrian is described in the following sections, and documented in papers 1 - 4. Of the lower Cambrian sequences listed above, I report results here from Central and South Australia, Newfoundland, Morocco, and the Siberian platform. Subsequent to my initial work in the Amadeus Basin (papers 1 and 2), Burek et. al. (1979) have extended it to the Ngala and Gorgina basins, and Lewis, VanAlstine and Shoemaker (pers. comm.) have compared it to the sequence in the Inyo mountains of California. Other work of relevance includes Gillett and VanAlstine (in press) and VanAlstine and Gillett (in press) on the magnetization of similarly-aged sediments in Nevada, and that of Kröner, et. al.

(in press) on the Nama group in Southwest Africa (Namibia). Using my results from the Amadeus Basin (papers 1 and 2) and his African data, McWilliams (1978) has suggested that the Australian- Antarctic and African- South American portions of Gondwanaland could not have joined until late Early Cambrian time. Of all these studies, only the magnetic directions from the Burin Peninsula (paper 4) are of clear secondary origin with no apparent primary components, and hence are of no use for magnetic polarity correlation.

As discussed in paper 3, most paleomagnetic studies do not fully utilize their data. For this reason, average paleomagnetic directions have been given where necessary in papers 1 - 4, and only polarity zonations are considered in the following review. Techniques outlined in paper 3 are currently being applied to the remaining localities, and the best estimates for average remanence directions will be reported separately. Finally, this research leads to a natural choice for positioning the Precambrian - Cambrian boundary, as will be discussed here last.

CONSTRUCTION OF A MAGNETIC TIME SCALE

A magnetic polarity time scale is intrinsically similar to radiometric and biologic scales because it is an attempt to position chronologically a series of geologic events in Earth history. Like the others, a polarity time scale must be carefully constructed from all of the available evidence; once constructed, it must continually be subjected to testing, improvement, refinement, and revision. The Precambrian - Cambrian boundary is far older than any known oceanic crust, and consequently the major features of the magnetic polarity variations cannot be inferred from sea-floor anomalies. Therefore, (1) the magnetization within each sequence must be tested to determine the time and nature of its origin, (2) the magnetic zonation must be constructed anew from each of many stratigraphic sequences, and (3) similarities in the stratigraphy and in the early (primary) magnetization between sequences within a basin or sedimentary unit must yield reproducible stratigraphic correlations. From these correlations, local polarity time scales are derived. This procedure, repeated anew for each basin examined, should converge on a common polarity time-scale that is a record of the behavior of the geomagnetic field, and that may be tied to the biologic and radiometric time scales. The magnetism which defines this time scale may then confidently be used on apparent polar wander tracks, and aid in paleogeographic reconstructions.

The Start: a magnetic zonation from the Amadeus Basin, Central Australia.

All paleomagnetic studies are based on remanent magnetization that resides in rock specimens. For the first step, specimens are desired for which the measurement of the remanent magnetism is consistent and reproducible. Paper 3 outlines the application of principal component analysis for this purpose

in paleomagnetic studies. Once found, these consistent magnetic directions must next be tested to determine when they were acquired. A fold test discussed in paper 1 compares the statistical grouping of magnetic vectors before and after correcting for structure, and shows that at greater than 99% confidence the sediments of the Amadeus Basin were magnetized prior to folding -- folding that occurred in the Devonian. Furthermore, magnetic polarity zones are truncated by a slight unconformity (Daily 1974) at the Precambrian-Cambrian boundary. This implies that the magnetism in the Precambrian rock is older than the unconformity, and hence must have formed shortly after deposition. The primary magnetization may now be used to construct a magnetic zonation through an iterative process. Paleomagnetic samples are collected continuously through a stratigraphic sequence at intervals that hopefully are much less than the average thickness of the polarity zones. Additional work may always increase the density if the initial sampling proves to be inadequate. In the Amadeus Basin, an average sampling interval of 1-2 meters was adequate to resolve the thicker magnetozones, although many small ones probably were missed in intervals of mixed polarity.

Intra-basin correlation. Polarity zonations constructed from the clean magnetic directions at each of three sampling localities in the Amadeus Basin are given in figures 2-5 of paper 2. The next step is to position the polarity columns according to the physical stratigraphy. In figure 6 of paper 2, the oldest rocks are of the Pertatataka Formation, followed by the Arumbera Sandstone and, above the disconformity, a number of laterally-equivalent lower Cambrian formations. Several features are apparent:(1)

the Pertatataka Formation at Areyonga has mixed polarities, whereas the stratigraphically overlying Julie member at Ross River is of entirely reversed polarity, (2) the Arumbera Sandstone at both Valley Dam and Ross River contains a thick normal magnetozone, and (3) all of the lower Cambrian formations have mixed polarities. At this stage, then, the long normal magnetozone in the Arumbera Sandstone exactly correlates this part of the sequence between Valley Dam and Ross River, and the mixed polarities correlate in a more general fashion the remaining intervals of stratigraphy. Firm paleomagnetic correlations are shown by the solid lines. A composite magnetic polarity zonation based on the Amadeus Basin stratigraphy has intervals that go from mixed polarity to reversed to normal and back to mixed.

Inter-basin correlations. Once a correlatable polarity sequence has been constructed within a sedimentary basin, the next step is to extend it outward into adjacent areas, if possible. Burek et. al. (1979) have done this for the Ngalia and Georgina Basins, both of which are N-NW of the Amadeus region. Their magnetostratigraphic correlation diagram (reproduced here as Fig. 1) a) clearly permits correlation of the Arumbera Sandstone with the Yuendumu I formation, and b) excludes a formerly proposed correlation of the Julie formation with the Wonnadinna dolomite. The guiding principle here is that two units of different (primary) magnetic polarities cannot be correlated.

Also within Australia, the lower Pound Quartzite of the Adelaide geogyncline yields a paleomagnetic pole reasonably close to that of the Amadeus Basin sediments (Fig. 8 of paper 1). Results from a few hand

samples which I collected across the Ediacara fossil horizon in the upper Pound Quartzite (Fig. 2 here) reveal a mixed polarity zonation which excludes it from correlation with either the lower Arumbera Sandstone (Arumbera I) or the Julie formation.

Intercontinental Correlations. The Australian magnetic polarity zonation is at the stage where it now could be used to help constrain intercontinental correlations. Ideally, it should be compared with results from another continent which both overlap it in time and which were based on a comparable data set. Although many units apparently overlap the Australian sequence in time, the paleomagnetic work is nowhere as advanced. Significant results, however, which indicate a start on the larger magnetostratigraphic problems have been obtained in the Inyo Mountains of California (Lewis, VanAlstine, and Shoemaker pers. comm.), the Siberian platform of the USSR, the Desert Range of Nevada (Gillett and VanAlstine in press), and the High Atlas mountains of Morocco. Additional paleomagnetic results have been reported from the Nama group of South Africa (McWilliams 1977) and from Labrador (Pearce 1978), but the samples were apparently not collected in a suitable fashion for polarity stratigraphy.

Inyo Mountains, California. Lewis, et. al (pers.comm.) sampled the middle and upper members of the Deep Spring formation at one location in the Inyo mountains of California, and compared it to the lower Cambrian sequence at Ross River in the Amadeus Basin; their correlation is shown here as Fig. 3. (As discussed in papers 1 and 2, Ross River has the best direct fossil control and paleomagnetic data of all localities in Central Australia.) Although

their work in California is not yet complete, the initial polarity sequence appears predominantly biased towards normal, and a fair match of polarity zones can be made. The first occurrence of key trace fossils, including Skolithos, Rusophycus, and Plagiogmus seem to be out of order, indicating that some of their first appearance horizons must be diachronous. These units probably correlate with the middle to upper Atdabanian stage of the Siberian Platform (A. Yu. Rozanov, personal comm.), although there is still some doubt.

The Siberian Platform. At the invitation of the Paleontologic Institute of the U.S.S.R., I was able to collect roughly 600 oriented paleomagnetic samples at six localities along the Lena River south of the city of Yakutsk (Fig. 4a). Samples were spread stratigraphically through strata ranging in age from the upper L. tortuosa subzone of the Tommotian stage through the middle of the P. pinus zone of the Atdabanian (Fig. 4b). A magnetic polarity zonation based on preliminary results from Zhurinsky Mys and Achchagy-Kyyry-Taas (Fig. 4a, #6 and 7) is given in Fig. 5. (The techniques used for obtaining these results are discussed in the first example of paper 3.) The 11 meters of late Tommotian strata at Achchagy-Kyyry-Taas contain a reversed-normal-reversed sequence that might correlate with an equivalently long normal zone in the more continuous magnetic sequence determined in the late Tommotian at Zhurinsky Mys, suggesting that the magnetization defining these zones is effectively of primary origin. Only a few portions of the magnetic zonation have wild changes in polarity, indicating either insufficient sampling density or complex magnetic overprints. These results from Zhurinsky Mys extend into the early L. poluseptus - R. zegebarti zone of the Atdabanian, and therefore could potentially overlap with the magnetic zonation from the lower Cambrian (Atdabanian?) sediments in Australia and California. Comparison of Figs. 3 and 5, however, shows

that they cannot overlap; the lower Atdabanian in Siberia (top of Fig. 5) is mainly of reversed polarity, while the lowest Cambrian units in Australia (bottom of Fig. 3) are biased towards normal polarity. Therefore, the strata in Siberia are represented in time by the unconformity shown on Fig. 1, and the first subsequent units in the Amadeus Basin were not deposited until post-lowest Atdabanian time.

Morocco. Precambrian - Cambrian boundary beds have been identified both in the High Atlas and Anti-Atlas mountains of Morocco (Choubert 1953; Sdzuy 1978). The geologic sketch map of northwest Africa shown on the top of Fig. 6 gives the location for two of the best-exposed localities in each area, Tiout in the Anti-Atlas and Ounein in the High Atlas. In both areas, the local stratigraphy is remarkably similar, going from stromatolitic units of the Serie lie de vin conformably on up into fossiliferous lower Cambrian limestone and dolomite. Unfortunately, the earliest trilobites and other fossils recovered tend to be new species, and do not permit precise correlation between the High Atlas and Anti-Atlas regions, nor do they allow reliable intercontinental correlation (Debrenne and Debrenne 1978).

Paleomagnetic samples were collected from both Ounein and Tiout; magnetic directions for those from the base of the Serie lie de vin at Tiout are discussed in the second example of paper 3, and the stratigraphic location of the rocks collected is shown on the lower half of Fig. 6. A paleomagnetic pole position calculated from this average direction lies on the Hadrinian segment of McWilliam's (1977) African apparent polar wander

curve, suggesting an age of about 700 m.y.; therefore the base of the Serie lie de Vin is probably of late Riphean age, as suggested for the stromatolites by Schmidt (1978). The polarity zonation from the samples shown on Fig. 7 is dominantly reversed, with at least three short normals. Although a precise correlation is not yet feasible, this sequence may overlap with the late Precambrian mixed polarity interval of VanAlstine and Gillett (1979). Results from the Calcaire superieur and Serie schisto-calcaire at Tiout will be reported elsewhere.

In the High Atlas mountains, the lower half of the Serie lie de vin is not exposed. Paleomagnetic samples therefore were collected stratigraphically upwards from the top 60 meters of the Serie lie de Vin and well on into the fossiliferous limestones. Facies of the lie de Vin generally behaved well upon thermal demagnetization as shown for a typical example in Fig. 8; the overlying limestone, however, appears to have a far more complex magnetic assemblage and are currently being re-examined using techniques outlined in paper 3. An apparent polarity zonation for Ounein is given on Fig. 9 alongside the stratigraphic column. A polarity change occurs roughly 8 meters above the base of the section, probably R-N, followed by 50 meters of normal polarity rock up to nearly the top of the Serie lie de Vin. Above this level the magnetization again becomes unstable although it seems to be of mixed polarity; further analysis along the lines of paper 3 is in progress.

At the current time, it is not known how to relate either of the Eocambrian sequences in the High or Anti-Atlas mountains to the Australian or Siberian polarity zonations discussed above. Sdzuy (1978) has argued

on the basis of the trilobite biostratigraphy that the earliest fossiliferous horizons in Morocco are equivalent to the lower Atdabanian; on the other hand, Rozanov and Debrenne (1974) assign these same units to the middle or upper Atdabanian stage on the basis of their Archeocyathids. To further complicate problems, Choubert (pers. comm.) has suggested the presence of a disconformity at the top of the Serie lie de Vin at Ounein, roughly at the point where the magnetic properties become complex. The paleomagnetic data are currently not able to suggest a solution to this problem.

A RECOMMENDATION FOR THE STRATIGRAPHIC LOCATION OF THE pЄ - Є BOUNDARY

The preceeding discussions clearly show that the magnetic polarity signature of Late Precambrian and Early Cambrian sediments may be of use in stratigraphic correlation. The next question to ask is whether or not it may be of use in selecting a boundary stratotype for the Precambrian - Cambrian transition. Because numerous authors have recently reviewed the lower Cambrian boundary problem (Cloud 1973; Cowie and Glaessner 1975; Cowie 1978), it is only worth summarizing here the most relevent IGCP-IUGS recommendations and decisions. These are:

- (1) The boundary should be fixed at a particular point within an internationally agreed upon stratotype sequence (the 'golden spike').
- (2) This point should provide the maximum potential for correlation, e.g., with reasonable accuracy, one should be able to locate it elsewhere, and
- (3) it should be "placed as close as is practicable to the base of the oldest stratigraphical unit to yield Tommotian (sensu lato) fossil assemblages". Note that it is not necessary to position the boundary entirely on the basis of Biostratigraphy; any and all means of correlation which are availible can and should be used. In the particular case at hand, the problem arises because there are no correlatable biostratigraphic horizons below the basal Aldanocyathus sunnaginicus zone of the Tommotian stage. (Presumably, before this time animals with shells did not exist.) Because the base of the Cambrian is felt to be the base of the Paleozioic as well (Cowie 1978), strong objection have been given to knowingly placing it above shelly fossils (Cloud 1973); hence, normal biostratigraphy cannot be used.

My proposed solution to this problem is to fix the boundary at a point within the stratotype sequence which corresponds to a geomagnetic reversal. Fig. 5 indicates that at least the upper half of the Tommotian stage is of mixed polarity, and there is every reason to expect a similar polarity zonation lower in the sequence. If one chose the first reversal below the earliest trace of the A. sunnaginicus zone, all the above requirements for a boundary stratotype would be met. If found elsewhere, the reversal and its adjacent polarity pattern could provide time correlation of far higher resolution than any other method. Ideally, the particular reversal chosen could have a distinctive transitional path of intermediate directions going from one polarity to the other. A candidate of this sort is the major R-N transition in the Arumbera Sandstone shown in the stratigraphic column on Fig. 1. This particular transition has been studied in detail at the Ross River locality, and Fig. 10 illustrates the observed sequence of intermediate directions and intensities. The transitional path is generally S-shaped, and should be uniquely distinctive over that part of Australia. If the geomagnetic field during this particular reversal retained its dipolar shape as has been suggested for some in the lower Ordovician by Khramov et. al. (1976), the transitional path would have the same shape at all locations on the globe, and thereby increase the confidence with which it could be recognized. Further, analysis of the transitional path of such a dipolar reversal would allow the relative paleolongitudes between continental blocks to be found, and uniquely fix their paleogeographic position. Finally, the reversed and normal magnetozones on either side of the reversal are unusually thick; thus it should be particularly easy to locate it in other areas.

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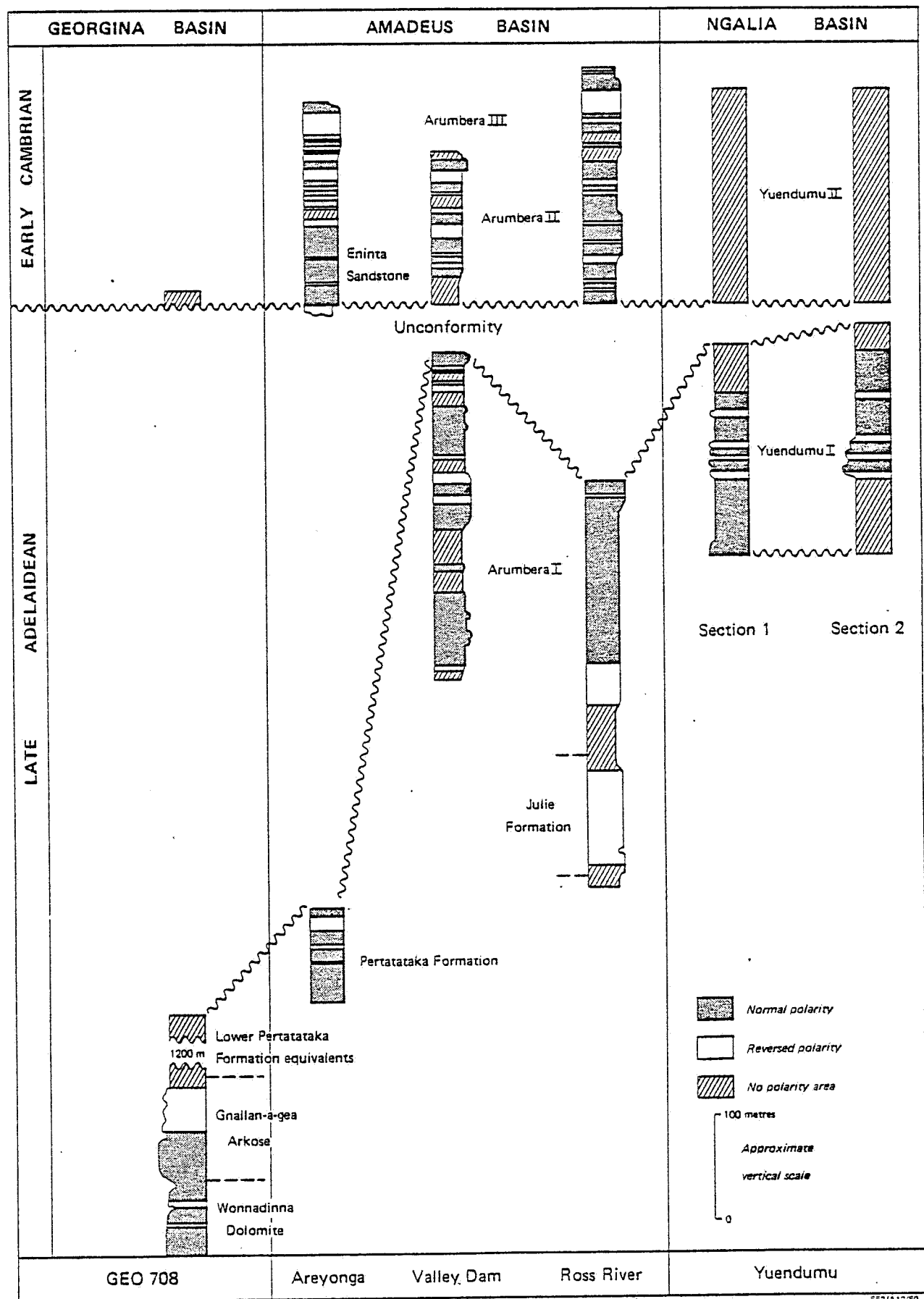


Fig. 1 Magnetic polarity sequences from the Amadeus, Ngalia and Georgina Basins. The Amadeus Basin data are from Kirschvink (1978).

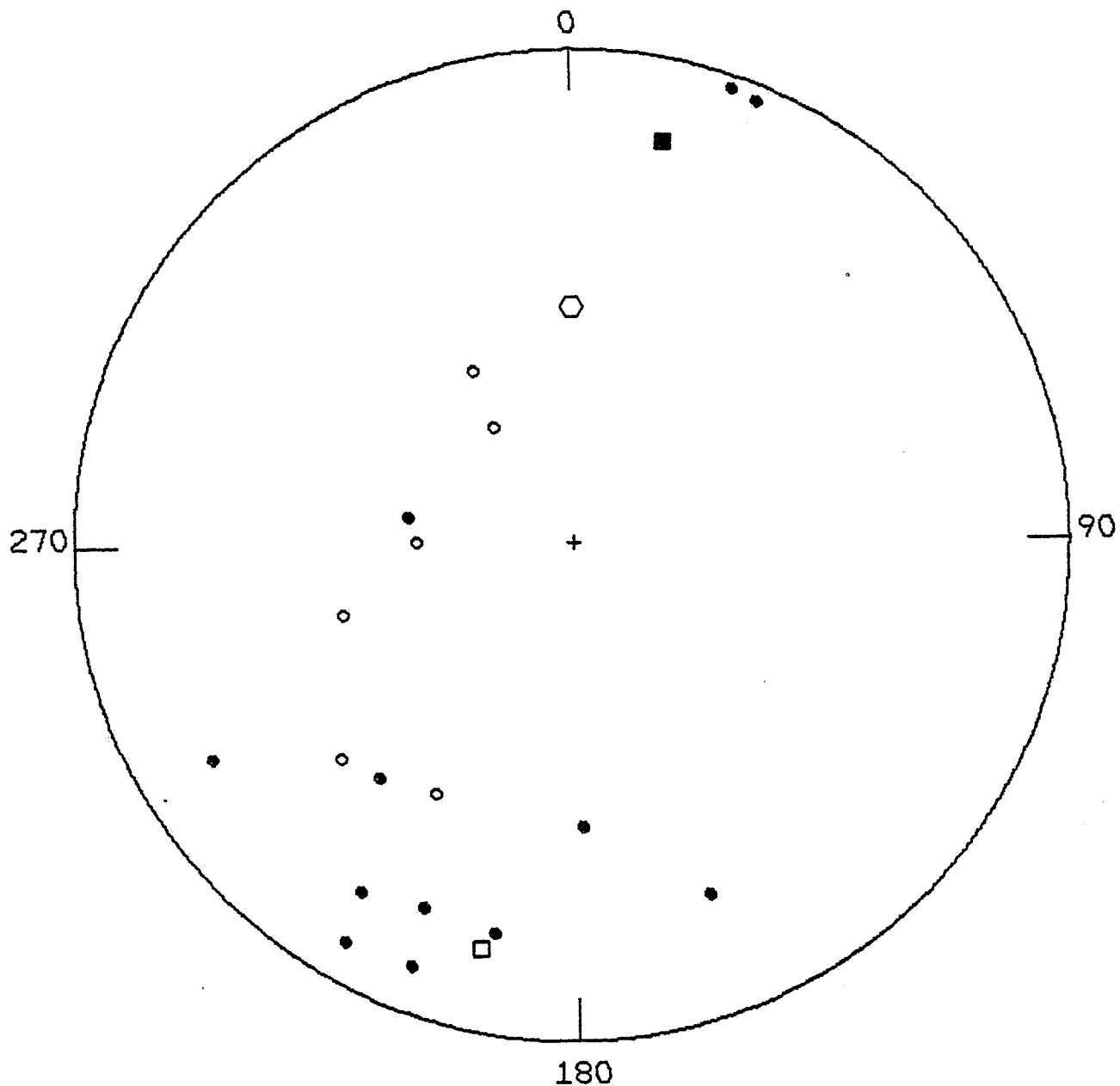


Figure 2

Preliminary, partially demagnetized paleomagnetic data from the Ediacara Horizon in South Australia. The open hexagon is the direction of the ambient field (open symbols imply negative inclination). The directions are generally streaking between present field and both normal and reversed Precambrian-Cambrian quasi-static directions (shown as squares), suggesting mixed polarities.

Fig. 3. Tentative magnetic polarity correlation between Early Cambrian sediments in Australia and California. If accepted at face value, the trace fossils Skollithos, Rusophycus, and Platygomus provide a rough correlation between the two localities, while the polarity zones refine it. Note that the apparent polarity sequence in both areas is dominantly normal with minor reversed zones.

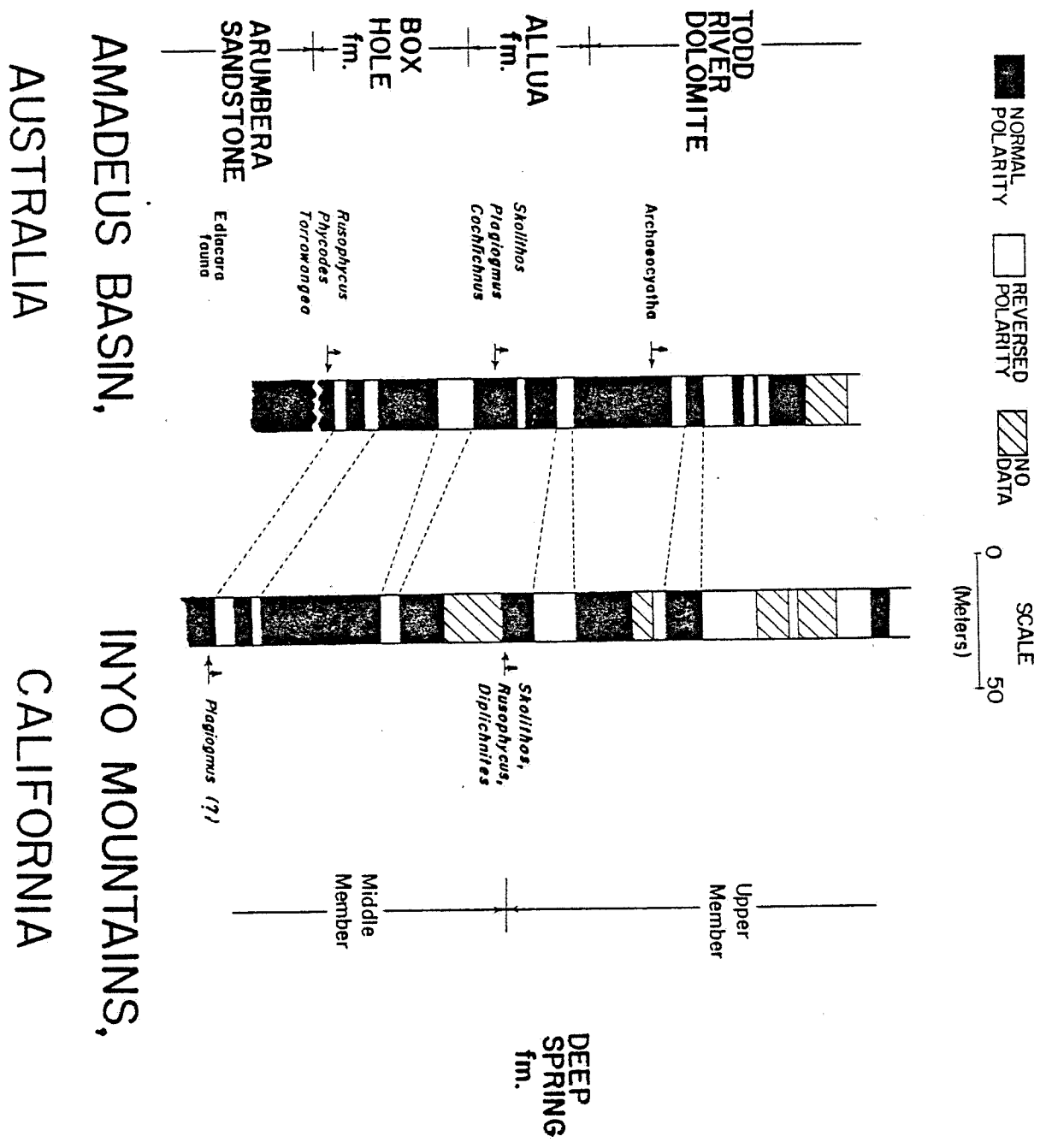
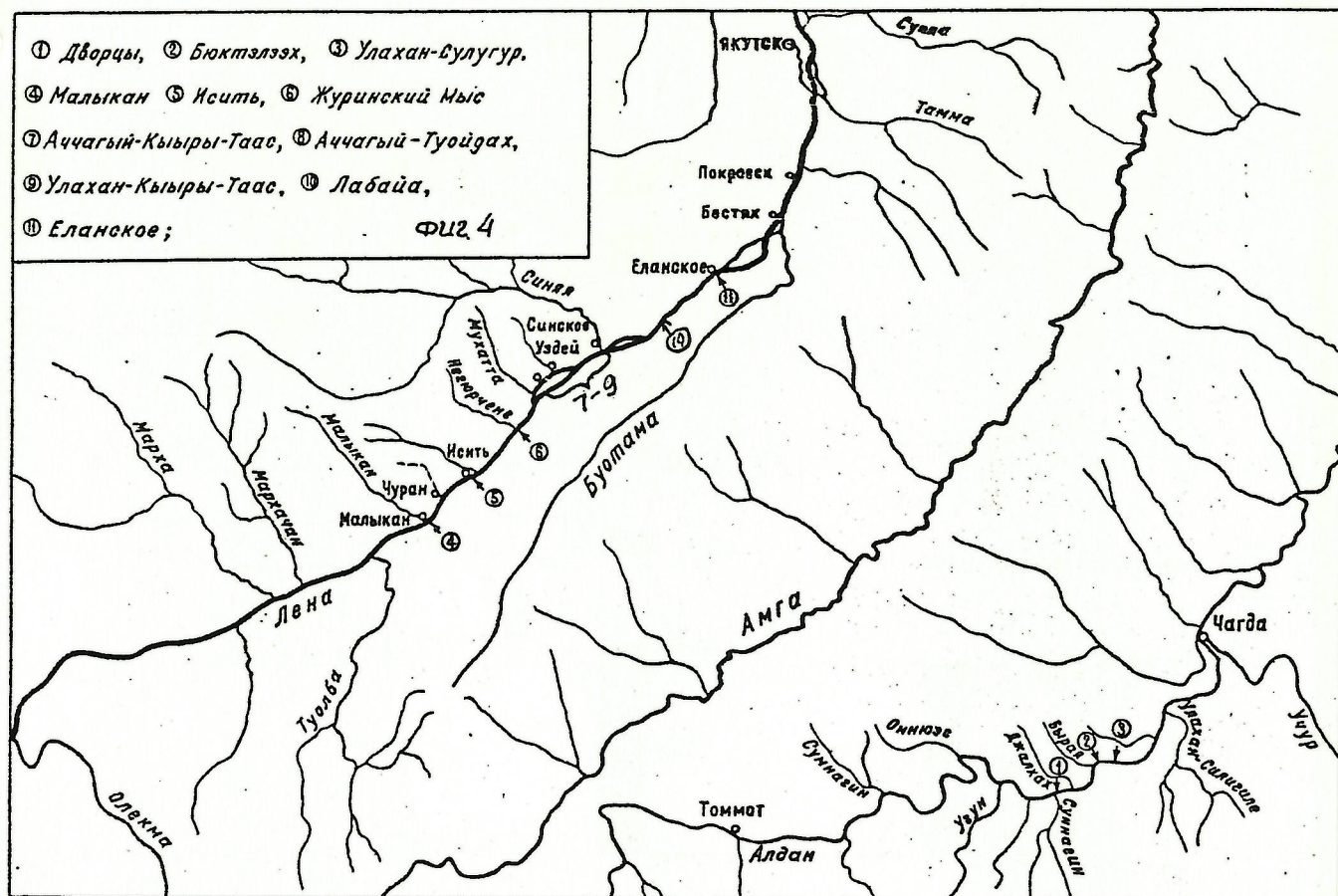


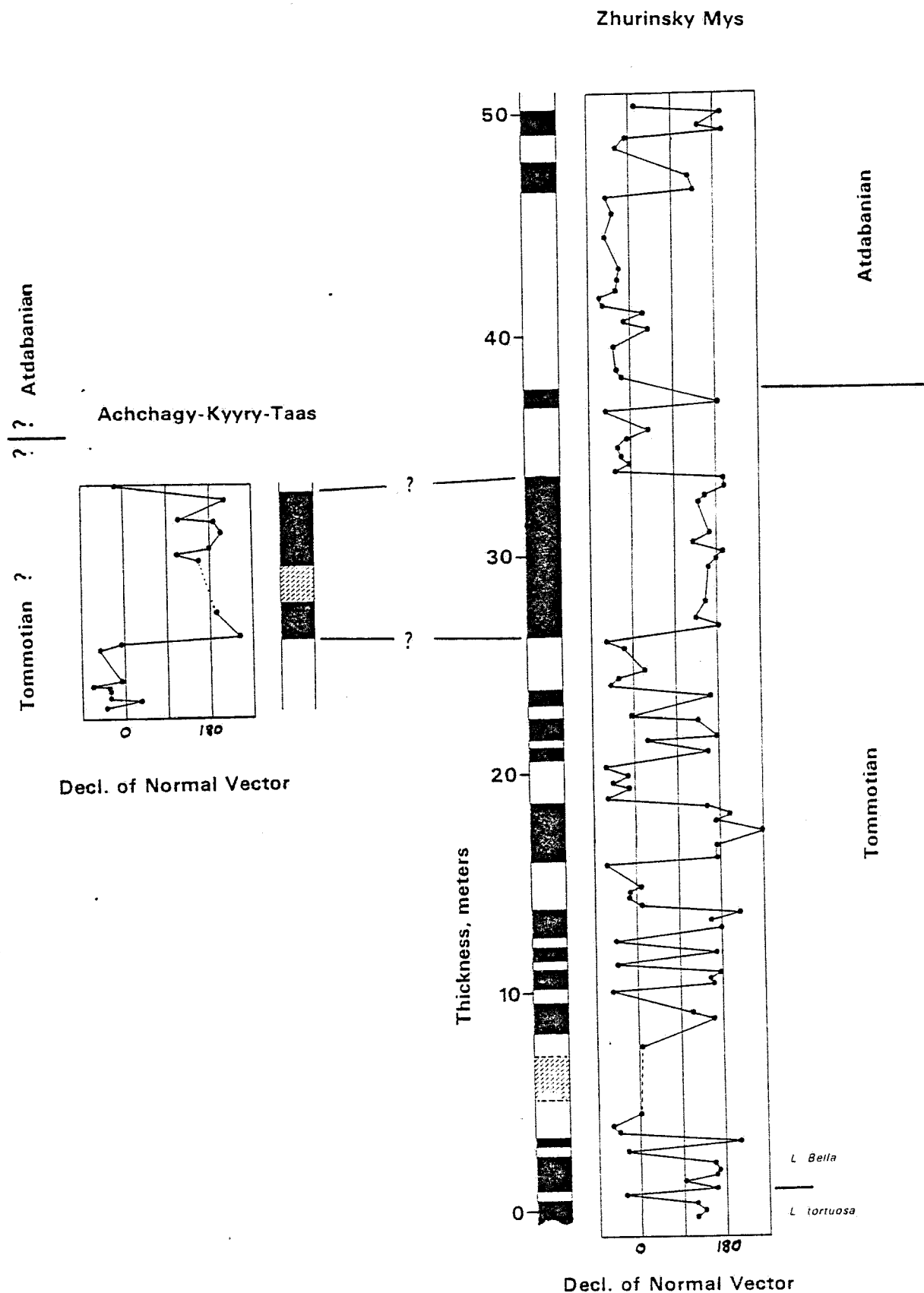
Figure 4. Sampling localities and intercontinental correlation diagram for the Siberian Platform, U.S.S.R. (From Rozaanov, et. al. 1969).



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СИБИРСКАЯ ПЛАТФОРМА SIBERIAN PLATFORM	РУССКАЯ ПЛАТФОРМА RUSSIAN PLATFORM	РАЙОН МОЗОА (НОРВЕГИЯ) MOZA DISTRICT (NORWAY)	АНГЛИЯ ENGLAND	МАРОККО MOROCCO	АВСТРАЛИЯ AUSTRALIA	КАЛИФОРНИЯ CALIFORNIA
ЛЕНСКИЙ LENIAN	ЗОНА PROTOLENUS	16a 16a 1a 1a2 1a1	Ad Ac5 Ac4	ИСАФЕНСКИЙ ЯРУС ISSAFENIEN	ОХА А А	ФОРМАЦИЯ ПОЛЕТА POLETA
АДАБАНАСКИЙ ATDABANIAN	ВЕРГАЛЬСКИЙ ГОРИЗОНТ VERCALE	16a 16a 1a 1a2 1a1	Ac, - Ac3 Ab4 Ab3	АМУСЛЕНСКИЙ АМУСЛЕКЕН ТИМЖИТСКИЙ TIMGITIEN	ВИЛЬКАВИЛИНА VILCAVILINA	JUDOMIA HOLMIA DAGUINASPIS ФОРМАЦИЯ КАМПИТО CAMPITO FALLOTASPIS
ТОММОТСКИЙ TOMMOTIAN	ЛЕНАИСКИЙ ГОРИЗОНТ LENAICUS	16a 16a 1a 1a2 1a1	Ab2 Ab1 Aa	АСАДАСКИЙ П.Я. ASADASIEN	ФОРМАЦИЯ ПАРАЧИЛНА PARACHILNA FORMATION	ДИПСПРИНГ DEER SPRING WUATTIA
ЮДОМИЙ YUDOMA	ВЕНД VEND	РИНГСАКЕР RINGSAKER		СУССКИЙ ЯРУС SOUSSIEN	ПАУНД POUND	?

Fig. 5. Preliminary magnetic polarity zonation from the Tommotian and lower Atdabanian stages of the Siberian platform.



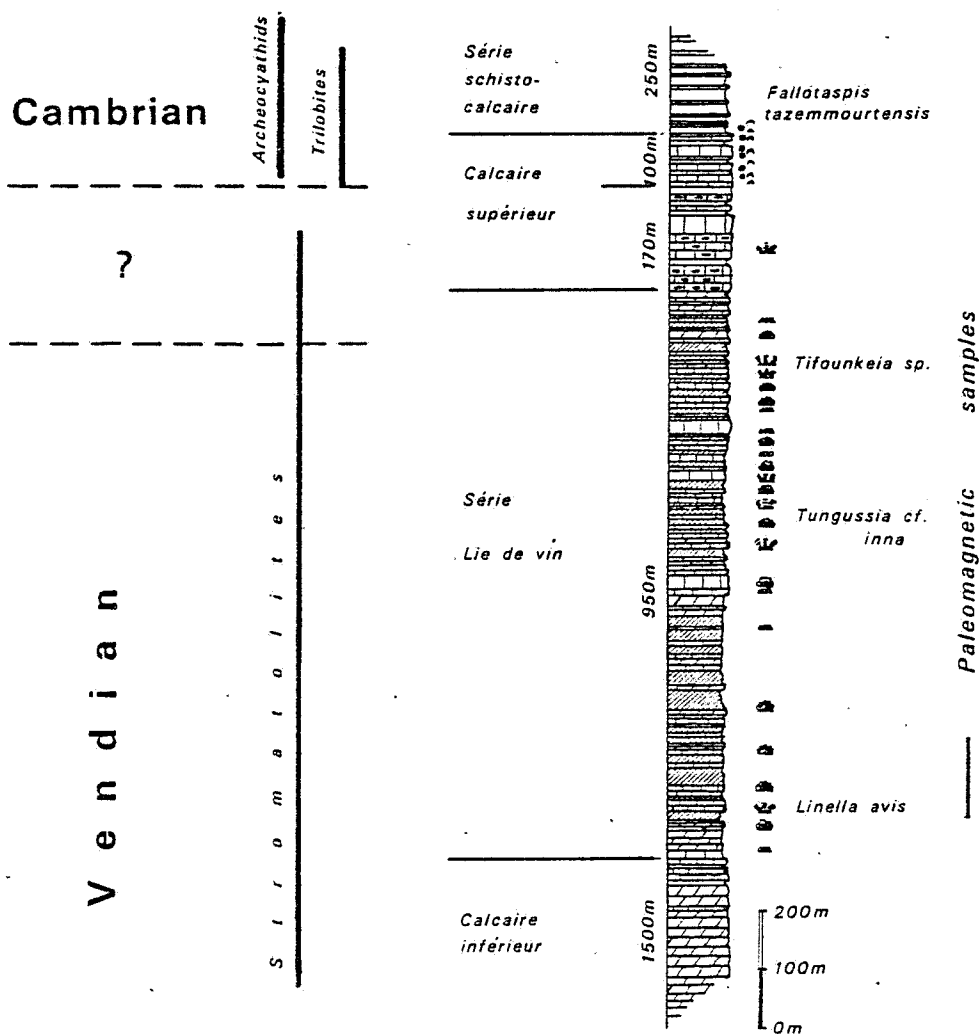
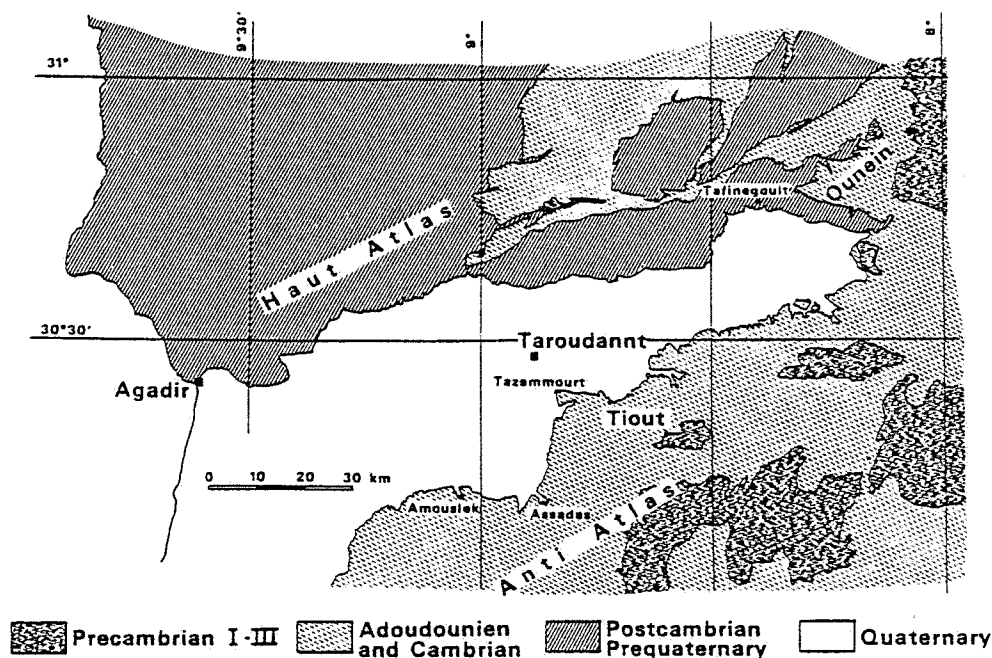


Fig. 6 Geologic location map and columnar section of Late Precambrian and Early Cambrian strata near Tiout, Morocco (After Sdzuy, 1978). The 28 paleomagnetic samples discussed in this report were collected as oriented cores drilled at evenly-spaced intervals spanning 70 meters in the base of the Série Lie de Vin. Tiout is located at 30.35°N Latitude and 8.67°W Longitude.

Figure 7 - Polarity structure in the Anti-Atlas Mountains of Morocco, near Tlout

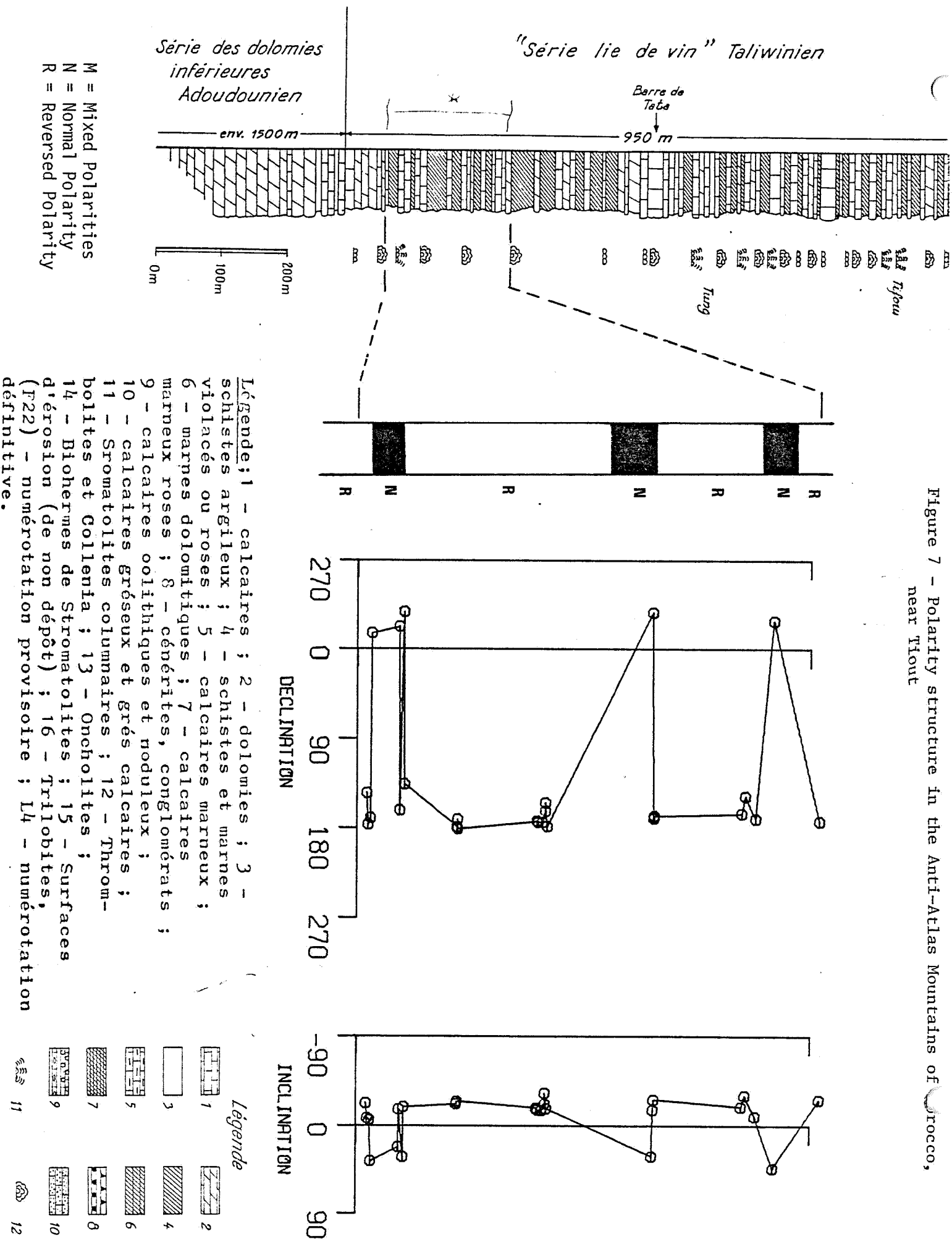
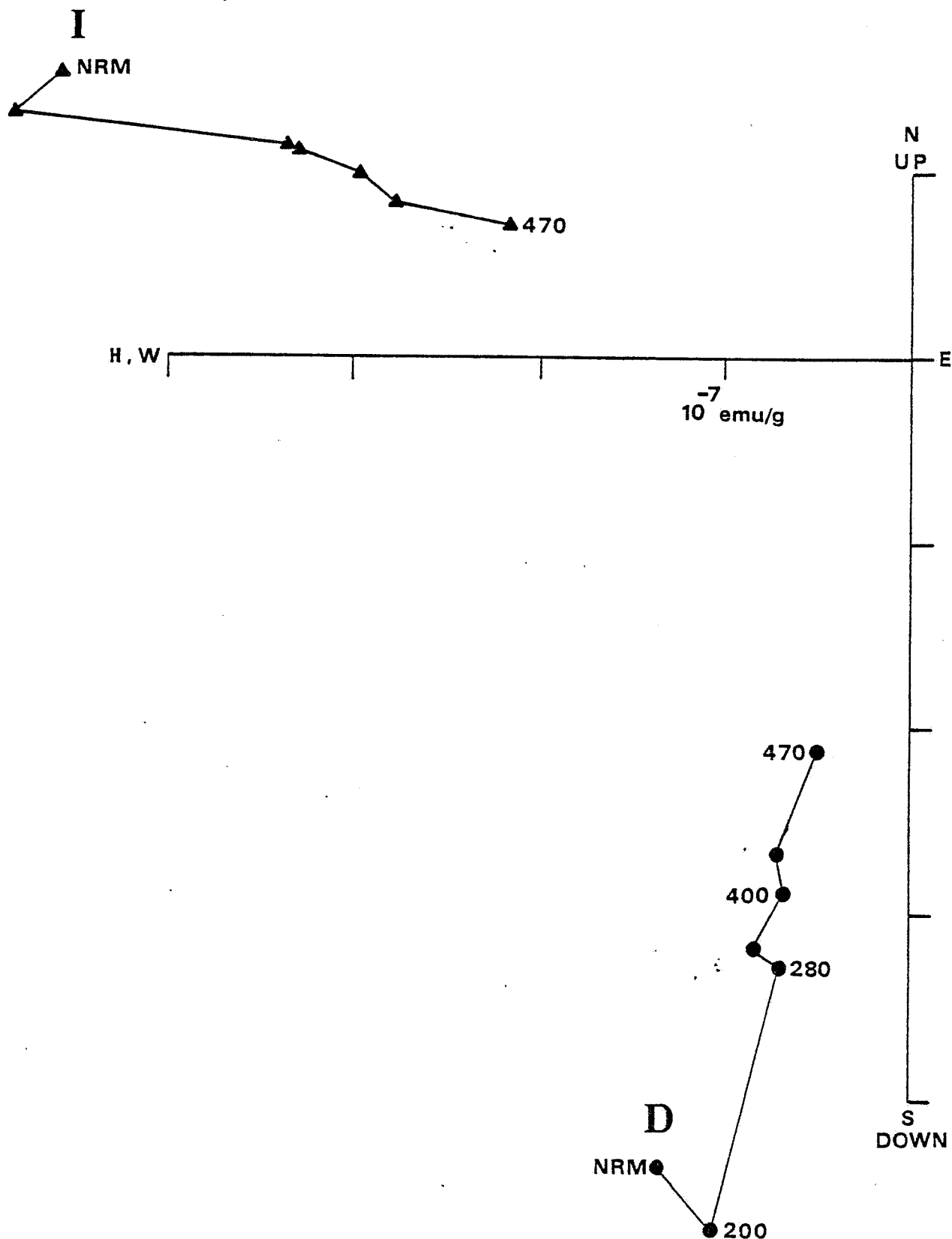


Fig. 8. Vector demagnetization diagram for a typical sediment of the Serie lie de Vin from Ounein (High Atlas Mountains, Morocco). Numbers alongside each path of the plot give the maximum temperature in °C. Directions have been corrected for local tilt of the strata.



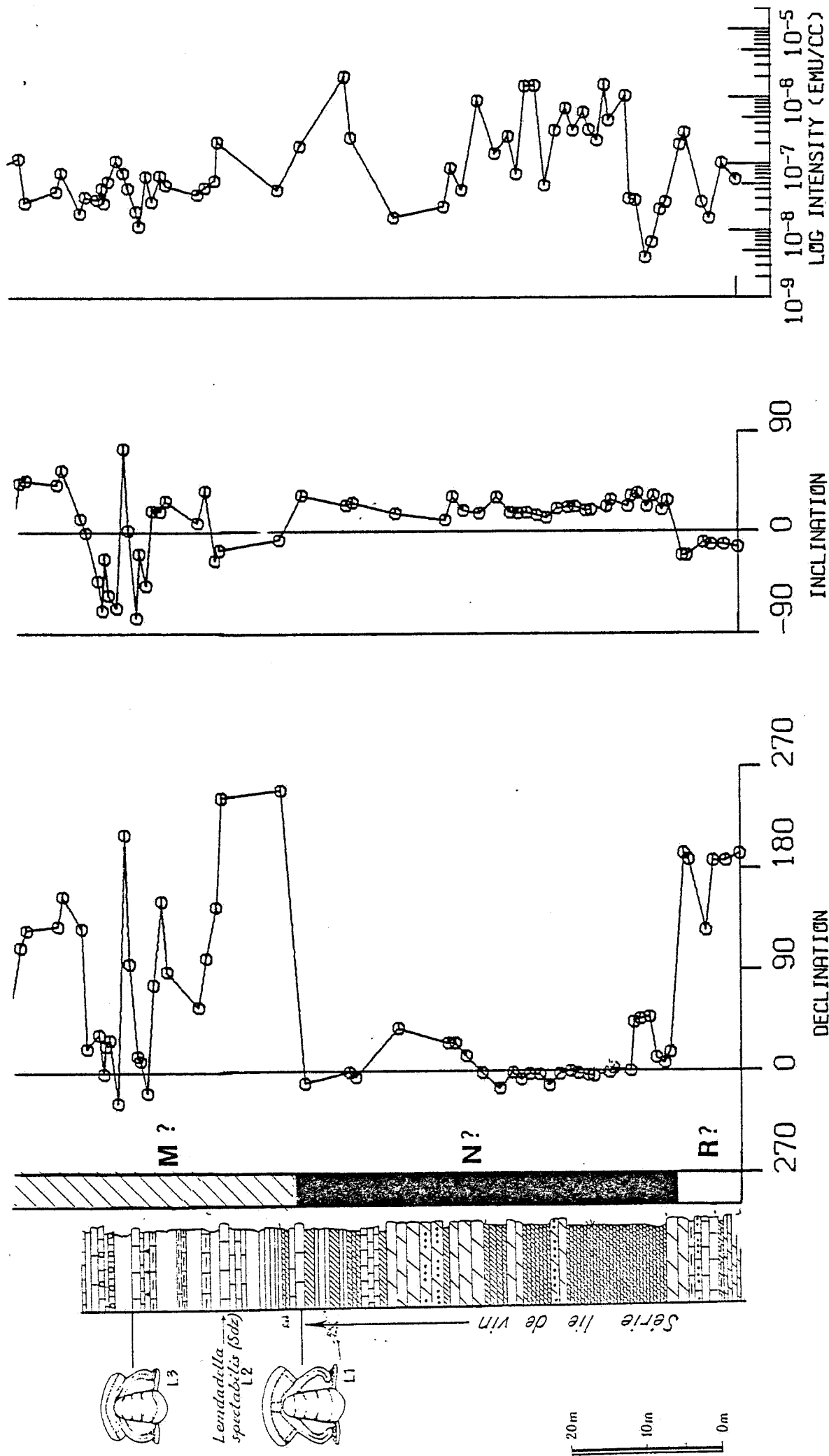
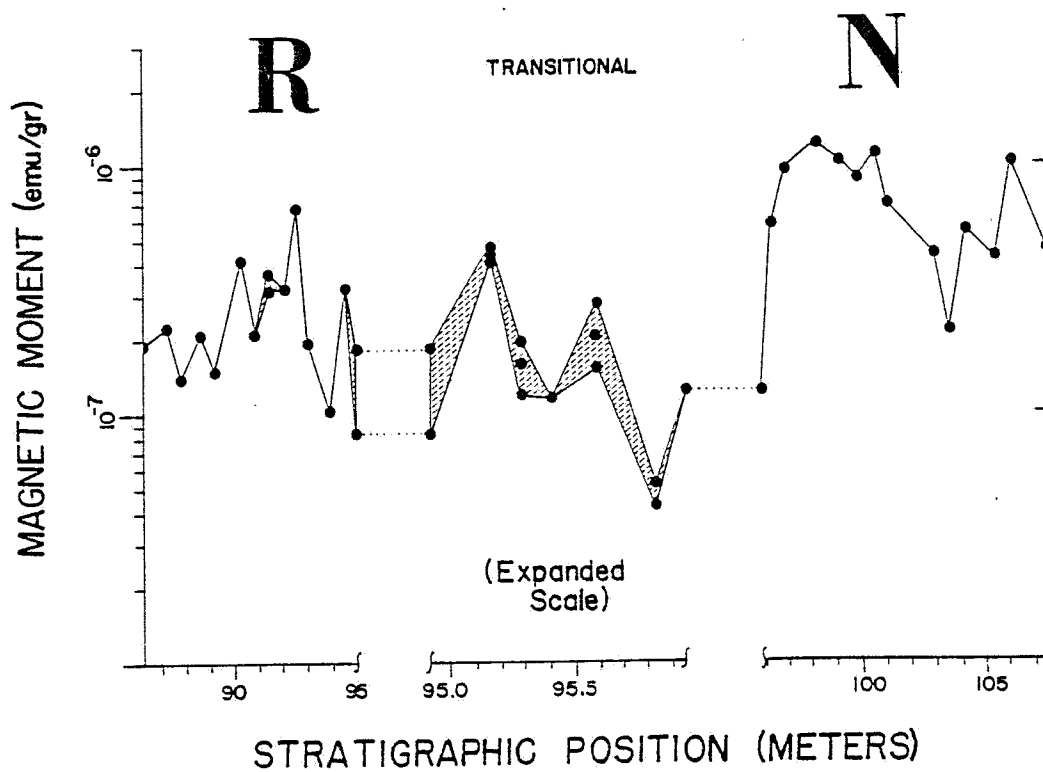
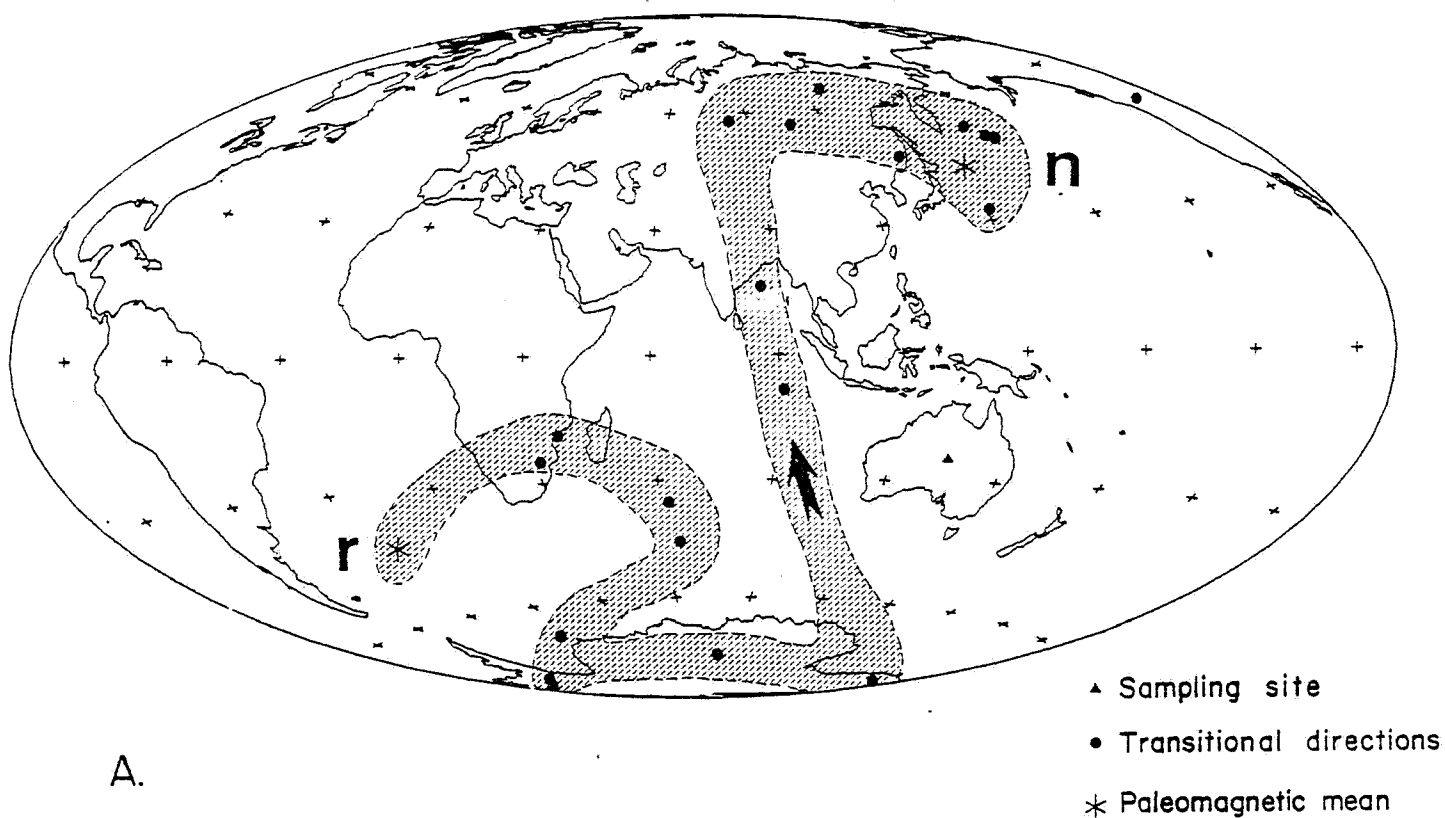
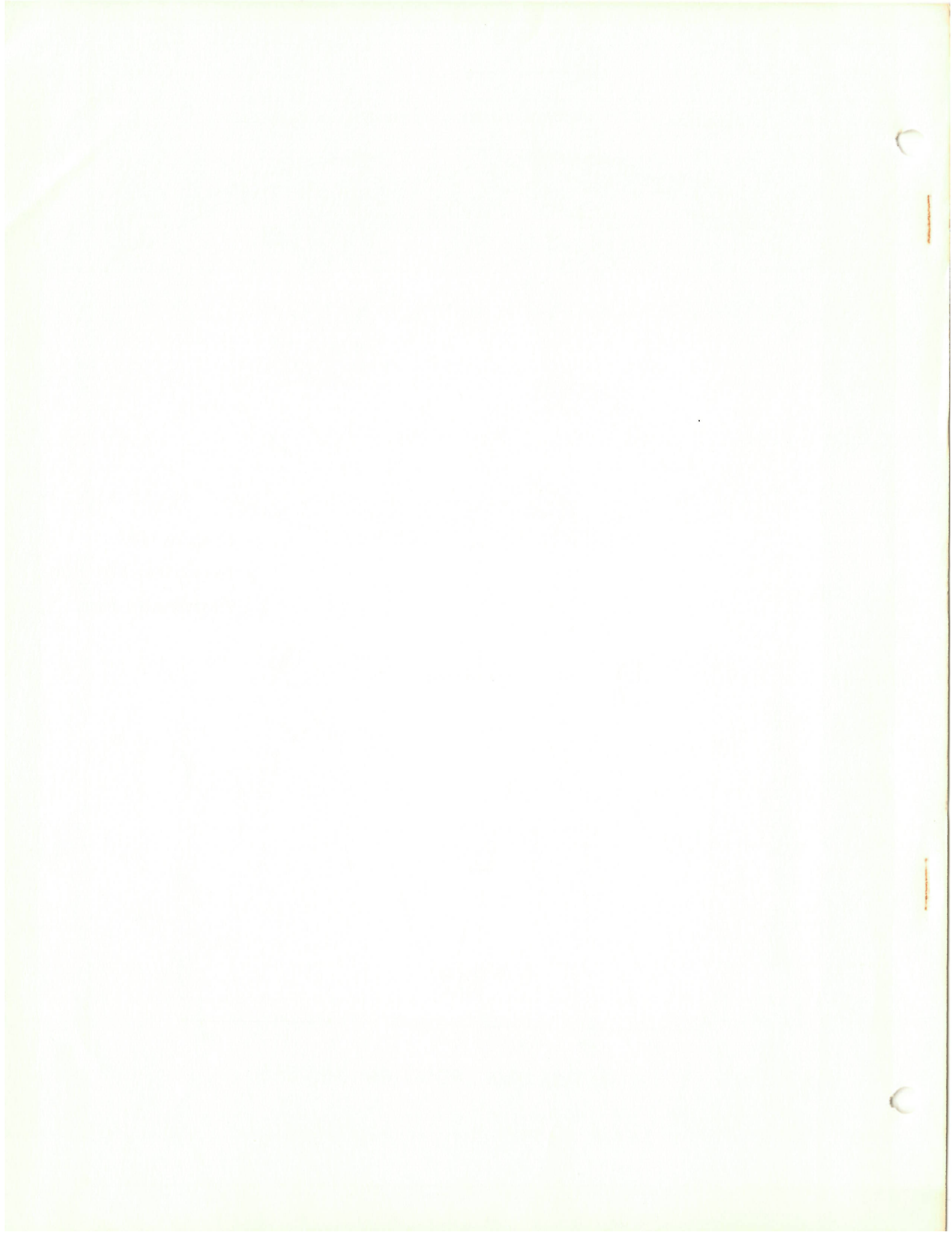


Figure 9 - Polarity structure from Precambrian to Cambrian sediments in the High Atlas Mountains of Morocco, near Ounein. Symbols and polarities are explained on Figure 7.

Fig. 10. The Arumbera Sandstone geomagnetic reversal.





The Least-Squares Line and Plane
And the analysis of paleomagnetic data

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ABSTRACT

The classic, multivariate technique of principal component analysis is used to find and estimate the directions of lines and planes of best least-squares fit along the demagnetization path of a paleomagnetic specimen, thereby replacing vector subtraction, remagnetization circles, and difference vector paths with one procedure. Eigenvalues from the analysis are the variance of the data along each principal axis, and provide a relative measure of colinearity or coplanarity which may be used to define a general paleomagnetic precision index.. Demagnetization planes found with principal component analysis may be used in place of difference vector paths for locating Hoffman-Day directions, avoiding unnecessary vector subtraction and intensity truncation steps. Two methods are discussed for jointly estimating an average remanence direction from demagnetization lines and planes.

1. INTRODUCTION

The Earth's magnetic field continually changes in polarity, direction, and intensity when viewed through geologic time. After its formation, a rock is exposed to a variety of changing magnetic fields. If at certain times during this history, it is subjected to physical or chemical conditions which alter its mineralogy or magnetic properties, it may completely or partially gain a new magnetic remanence. Typically, this new remanence will form a discrete component parallel to the local geomagnetic field direction and add vectorially to any of the original remanence remaining in the rock. Although it is desirable in most paleomagnetic studies to find the direction of all these various components, techniques currently in use do not exploit all of the available data (especially intensity). Ideally, analytical methods at both the specimen and sample levels should be based on as much of the original magnetic information as possible, with minimal assumptions. To accomplish this goal, it is necessary to first apply the classic multivariate technique of principal component analysis to collinear and coplanar points along a specimen's demagnetization path. Principal component analysis provides estimates of relative collinearity or coplanarity of the data, as well as directions of best least-squares fit. Next, if groups of lines and planes of specimens from different samples respectively yield clusters (bipolar with mixed N & R data) and girdles of directions on a stereonet which indicate a common magnetic component, all of the directions should be combined into a joint estimate for the average remanence. Techniques for both of these are discussed and developed in sections 2 through 6, and applied to paleomagnetic examples in part 7.

Although principal component analysis is based partly on least-squares minimization, it should not be confused with the exponential least-squares modeling technique of Stupavsky and Symons (1978). Their technique presumes

a lognormal grain size-coercivity distribution in space and requires systematic AF demagnetization data; when applicable, their exponential models may have greater ability to resolve superimposed components. Many sedimentary rocks however do not respond well to AF demagnetization, and the magnetic grain-size distributions of freshwater and marine sediments may for example be disturbed by a discrete, single domain spike of biogenic magnetite (Frankel, et al., 1979; Kirschvink and Lowenstam, in press). Techniques discussed in this paper are generally applicable to all remagnetization data regardless of demagnetization procedure, magnetic mineralogy, type of remanence, or grain-size distribution.

2. SEPARATION OF MAGNETIC COMPONENTS

Directions of magnetic components within a rock may be separated by progressively destroying in small increments the natural remanence through heating, AF demagnetization, chemical leaching, or other demagnetizing procedures; these experiments attempt in part to reverse in the laboratory the mechanisms by which the remanence was gained in nature. The orientation and intensity of the magnetism measured after an incremental demagnetization experiment constitutes a magnetic vector, the 'tip' of which forms a point in magnetic 3-space; the set of all such points produced during progressive demagnetization defines the demagnetization path for the specimen. Conversely, a point in magnetic 3-space represents a vector pointing from the origin to it. Ordered points along these paths conceptually fall into three geometric groups: lines, planes, and 3-dimensional curves. A series of points which are collinear usually indicate the progressive removal of one magnetic component; the direction of the line containing them is, of course, parallel to the discrete magnetic vector that was removed. Coplanar points are likewise found when two discrete magnetic components are simultaneously removed in differing ratios; this plane is best described by its pole (perpendicular direction). It should be emphasized that the direction found for a line on a demagnetization path is an estimate of where the remanence is, while a pole to a demagnetization plane is an estimate of where the remanence is not. Both are of use in paleomagnetic studies as will be discussed in sections 5 and 6. The third category, a 3-dimensional curve, is produced by the simultaneous, progressive removal of more than two discrete magnetic components. These three geometrical groups may be encountered individually, or together in any order along the demagnetization path of a paleomagnetic specimen, and it is important in nearly all such studies to recognize the lines and planes within the data and estimate their direction.

Many techniques have been proposed and are currently used in paleomagnetic studies to locate and estimate the direction of colinear and coplanar points along a demagnetization path. The most popular include the best demagnetization step, stable end point, orthogonal projection, vector subtraction, remagnetization circles, and difference vector paths (for example Collinson, et al., 1967; Zijdeveld, 1967; Khramov, 1958; Halls, 1976, 1978; and Hoffman and Day, 1978). The success of these paleomagnetic techniques is generally unquestioned; they often yield reasonably accurate estimates of the desired magnetic directions. However, all of these techniques either use only one or two of the data points (such as vector subtraction) or exclude a major part such as the intensity (remagnetization circles and difference vector paths). The classic multivariate technique of principal component analysis (Pearson, 1901; Hotelling, 1933) was developed to handle this type of data without such unnecessary exclusion, but it has not been used in progressive demagnetization studies. Because recent technological developments have substantially reduced the effort required to progressively demagnetize and measure a rock specimen (Molyneux, 1971; Goree and Fuller, 1976), large amounts of data are rapidly becoming available. It therefore seems timely to replace the graphical and vector-subtraction techniques currently in use with the analytic rigor of principal component analysis. For lines and planes, this method provides directions of best least-squares fit to the data as well as a measure of their collinearity or coplanarity.

3. PRINCIPAL COMPONENT ANALYSIS

Principal component analysis is simply a linear transformation of the orthogonal coordinate axes to a new orthogonal reference frame that corresponds to the geometry of the data set. The origin in the new system corresponds to the 'center of mass', while the new axes are positioned by least-squares to best fit the data. Each axis in the new reference system has associated with it a measure of the variance (σ^2) about the mean in that particular direction; two of the axes are positioned to correspond to the maximum and minimum direction of variance, while the other (in the 3-dimensional case) is intermediate. Through the use of Lagrange multipliers, it can be shown that the principal axes parallel the eigenvectors of the matrix of sums of squares and products,

$$H = \begin{bmatrix} \Sigma(x_i - \bar{x})^2 & \Sigma(x_i - \bar{x})(y_i - \bar{y}) & \Sigma(x_i - \bar{x})(z_i - \bar{z}) \\ \Sigma(x_i - \bar{x})(y_i - \bar{y}) & \Sigma(y_i - \bar{y})^2 & \Sigma(y_i - \bar{y})(z_i - \bar{z}) \\ \Sigma(x_i - \bar{x})(z_i - \bar{z}) & \Sigma(y_i - \bar{y})(z_i - \bar{z}) & \Sigma(z_i - \bar{z})^2 \end{bmatrix} \quad (1)$$

where $P_i = [x_i, y_i, z_i]$, $i = 1, N$ are the N data points in the old coordinate system and $U = [\bar{x}, \bar{y}, \bar{z}]$ is the position of the origin for the new system.

Eigenvalues ($\lambda_{\max}$, λ_{int} , $\lambda_{\min}$) associated with each eigenvector are the variance of the data along the new axes. If the points all lie precisely along a line, for example, all of the variance is parallel to it. One principal component completely represents the data, and the dimensionality of the total system may be reduced. In this case two eigenvalues will be zero while the third is large, one eigenvector will parallel the line and the other two will be at arbitrary right angles to it. Similarly, there is no variance perpendicular to a plane which contains all of the data; the pole to this plane is the eigenvector associated with the zero variance.

This mathematical procedure is equivalent to finding the lines and planes of best least-squares fit as derived by Schomaker et al., (1958) and Blow (1959).

If the data are treated as point masses, the mathematics are equivalent to finding the principal axes of inertia about the point U. Note that if U is taken as some point other than the center of mass, the lines and planes will still be constrained to pass through it while at the same time minimizing the sum of squared deviations. Matrix H is also equivalent to Watson's (1960) matrix of sums of squares and products if each data point, P_i , is truncated to unit distance from the origin and the point U is taken as [0,0,0]. In this form, H serves as the basis for Dimroth-Watson and Bingham spherical statistics (Watson, 1960, 1965, 1966; Dimroth, 1963; Bingham, 1964, 1974). Most computing centers have standard software programs for computing eigenvectors and eigenvalues from symmetric matrices, the IBM Scientific Subroutine Package (SSP) routine EIGEN is one such program.

4. APPLICATION TO PALEOMAGNETICS

4.1 Location of lines and planes.

Groups of points which belong to lines and planes along a demagnetization path have been recognized in most paleomagnetic studies using graphical techniques. Lines are recognized as straight segments after orthogonal projection (Zijderveld, 1967) or as stable endpoint clusters on a stereonet. Planes which pass through the origin can be found by great circle arcs left on a stereonet (Khramov, 1958; Halls, 1976, 1978), and planes which do not include the origin have been recognized by great circle paths produced by successive difference vectors (Hoffman and Day, 1978). Although reasonably accurate, this eyeball interpretation is not really necessary. Principal component analysis can be used to group a set of points along a demagnetization path into the three categories discussed earlier on the basis of their eigenvalues;

$\lambda_{\max} \gg \lambda_{\text{int}} \gtrsim \lambda_{\min} \approx 0$ implies that the data are grouped on a line,
 $\lambda_{\max} \gtrsim \lambda_{\text{int}} \gg \lambda_{\min} \approx 0$ implies a plane, and $\lambda_{\max} \gtrsim \lambda_{\text{int}} \gtrsim \lambda_{\min} \gg 0$ suggests a 3-dimensional curve. A simple, easily-computerized procedure which can be used to locate linear or planar groups of points along a demagnetization path is explained on the flow diagram shown in Fig. 1. Once this, a similar algorithm, or an eyeball, has identified groups of collinear or coplanar points, principal component analysis may be used to find the direction of best fit to a line or the pole to a plane. Throughout the rest of this paper, these collinear and coplanar groups of points will be referred to as demagnetization lines or demagnetization planes, respectively.

4.2 Criteria for determining linearity or planarity.

A numerical search of the type outlined on Fig. 1 needs a uniform criterion for deciding the linearity or planarity of a group of points. Because the eigenvalues from a principal component analysis are the variance in each principal direction, a simple approach is to ask what the Maximum Angular Deviation

(M.A.D.) of the direction would be if the fit along each axis was off by one (or an equal amount of) standard deviation (σ). By analogy with a long rectangular box of dimensions $\sigma_{\max}$, σ_{int} , $\sigma_{\min}$, this characteristic angle of equal deviation for a line would be that between the central diagonal and a long edge, or

$$\tan^{-1}(\sqrt{\sigma_{\text{int}}^2 + \sigma_{\min}^2} / \sigma_{\max}),$$

or

$$\tan^{-1}(\sqrt{(\lambda_{\text{int}} + \lambda_{\min}) / \lambda_{\max}}).$$

By considering a thin rectangular box with a diagonal plane, the maximum angle of deviation for the pole to a demagnetization plane is similarly found to be

$$\tan^{-1}(\sqrt{\lambda_{\min} / \lambda_{\text{int}} + \lambda_{\min} / \lambda_{\max}}) \quad (3)$$

Note that only the relative magnitudes of the three eigenvalues are important. Although these angles are not strict confidence limits, small values respectively indicate collinearity or coplanarity of the data and may be used in a numerical search (Fig. 1). The eigenvalues thus provide a basis for accepting or rejecting data from a particular specimen. Measurement error and the magnitude of superimposed magnetic components are the only factors which will increase the variance and lead to larger M.A.D. values. Groups of points with values above a specified standard therefore may be omitted from further analysis, leading to the possible exclusion of entire specimens which are found to possess neither collinear nor coplanar points. In this sense, the maximum angle of deviation is a general paleomagnetic precision index and may serve in place of stability indices used by earlier workers (Tarling and Symons, 1967; Ade-Hall, 1969; Briden, 1972; Symons and Stupavsky, 1974; see also the critique by Andel, 1970). Unlike other indices, the M.A.D. is purely geometric and bears little or no relationship to the demagnetization procedure used or to the intensity of the demagnetizing process between

measurements. M.A.D. values change little by the addition of new points beyond the stage at which the continuous shape of the demagnetization path is approximated by the data along it. The optimum number of demagnetization steps for a given specimen depends upon its magnetic complexity; three points (including the origin) are the minimum number necessary to check for collinearity, while four are needed to check for coplanarity. For example, each component from a 3-component specimen conceivably could be specified by 8 measurements plus the origin (9 total points) if their coercivity or blocking temperature spectra did not overlap.

4.3 Anchoring lines and planes to the origin.

Within whichever error limits are used, if the origin happens to lie on a demagnetization line or plane a slight analytical variation may be substituted for computing the principal direction of best fit. Physically, inclusion of the origin for a line implies that only one component remains in the rock; for a plane only two remain. All others, if there were any, have been removed by demagnetization. The difference in technique arises because the origin is an exact theoretical point on all demagnetization paths. (Completely demagnetized specimens should have no remanence.) In this case, use of the origin instead of the centroid as the point U in eq. (1) mathematically forces the line or plane of best fit into agreement with the physical interpretation. The centroid is used for the general case because it is the best available estimate of a point which lies on the line or plane of best fit; in the particular case at hand the origin is theoretically better. In practice, these demagnetization lines and planes anchored to the origin have one less degree of freedom than the offset, free versions, somewhat reducing their directional scatter. An anchored demagnetization line is the least-squares generalization of a stable end-point direction while an anchored plane is the similar generalization of a remagnetization circle.

5. GENERALIZATIONS OF ANALYTICAL TECHNIQUES INVOLVING DEMAGNETIZATION PLANES

5.1 Comparison of planar methods.

Before techniques which have in the past been used for analysis of coplanar data are compared, it seems worthwhile to illustrate interrelationships between the various methods. The solid curve on the top half of Fig. 2 is a schematic drawing of a planar demagnetization path. Arrows which connect the origin of the unit circle to the path are the remanence vectors measured directly after each demagnetization step. A free demagnetization plane in this case would pass through the centroid ($U = \oplus$) and be fit to all known points (NRM, A, B, ... F, Origin). The direction of the pole is found by principal component analysis on the original data. An anchored demagnetization plane would use the origin instead of the centroid as point U in eq. (1), and be fit to points NRM through F along the demagnetization path. For a remagnetization circle (Khramov, 1958; Creer, 1962; Halls, 1976, 1978), only the direction of each remanence vector is considered as would be viewed on a stereonet. On Fig. 2, small open squares are drawn around points where the remanence vectors intersect the unit sphere; a plane constrained to pass through the origin is fit to these normalized directions. Finally, the last technique which has been proposed for determining the orientation of these coplanar points is to consider the path of successive difference vectors (Hoffman and Day, 1978). On Fig. 2, these coplanar vectors are shown as dashed arrows which sequentially connect adjacent points along the demagnetization path. After regrouping so that they start at the origin as shown on the bottom circle, a new plane passing through the origin can again be fit to the normalized directions shown as the circled points on the unit sphere. This new plane should parallel the old. Note that the normalization step is not necessary; an anchored plane may be fit directly to the difference vectors.

The philosophy underlying the truncation of vectors to unit length is a

further difference which should be discussed in the comparison of these techniques. For vector data from a single paleomagnetic specimen, this step at first seems to be unnecessary. Intensity is as much a part of vectors as is their direction; its omission requires at least some justification. One situation in which truncation might be advantageous is where a component of particular interest is much smaller than the other. Remagnetization circles in this case may discriminate against the strong component, and enhance the relative effect of the smaller one (Example 7.1). On difference vector paths, however, vectors of small magnitude have far more scatter in direction due to subtraction errors than do the larger vectors; in this case truncation to unit length clearly worsens the fit. If run without the truncation, a fit of the vector difference plane would weight the vectors according to their intensity and reduce this scattering error. These two types are respectively referred to as 'difference vectors' and 'difference-vector paths', and will be examined further in the first example.

Of these various techniques, only the free demagnetization plane and the vector difference methods can determine the orientation of a plane which does not include the origin; the vector subtraction process in this latter method, however, by itself will increase the scatter in the data and thereby reduce the accuracy of fit. Poles to demagnetization planes can be used in place of those from both remagnetization circles and vector difference paths in the two techniques discussed next.

5.2 Separation of multicomponent NRM: Hoffman-Day directions.

Hoffman and Day (1978) recognized that it is sometimes possible to isolate uniquely the direction of a magnetic component which contributes to a demagnetization path even though it may never by itself form a straight line segment. Their original technique used two difference-vector paths from a single specimen which converged (as viewed on a stereonet) at a common

direction. Fig. 3 shows how these Hoffman-Day directions may be found using demagnetization planes. The overlap of three components A, B, and C is least in row (A), and greatest in row (D), as shown by the stability spectra in the first column of figures. The second column shows the 3-dimensional shape of the corresponding demagnetization path in 3-space, and the third plots the difference vector paths one would observe on a stereonet (used by Hoffman and Day). Numerals along each diagram indicate the number of different components simultaneously being removed at that point. Adjacent component pairs which form planes [A,B] and [B,C] in rows (B) to (D) result in two great-circle difference-vector paths which intersect at the direction of component B; thus the direction of B may be found even when it is not uniquely exposed as in rows (C) and (D).

Neighboring demagnetization planes can be used in place of the difference-vector paths, however, because the intersection line of planes [A,B] and [B,C] on Fig. 3 is parallel to component B. (Two planes intersect along a common line; the common line in this case is B.) This is clear for Fig. 3 (A) where the planes [A,B] and [B,C] are defined by pairs of the 3 straight line segments. Since corresponding planes in each column of Fig. 3 are parallel (e.g. [A,B] from 3(A) is parallel to [A,B] from 3(B), etc.) the direction of B may be recovered even for the example of 3(D) where there are no linear segments. If $P_{[A,B]}$ and $P_{[B,C]}$ are the respective poles to these demagnetization planes, the direction of B is given by the vector cross product $P_{[A,B]} \times P_{[B,C]}$. In general, if a single paleomagnetic specimen has K components which overlap as shown in Fig. 3, the direction of K-2 of them may be found with this method. Note that use of demagnetization planes avoids the vector subtraction and intensity truncation steps that increase noise on vector difference paths (see Example 7.1).

5.3 Intersecting demagnetization planes.

Situations occasionally arise in paleomagnetic studies where most specimens

share a common magnetic component, but have between them a number of variable, randomly directed overprints. Progressive demagnetization of these specimens then may yield remagnetization circles on a stereonet which tend to converge or diverge from the common direction. Halls (1976, 1977, 1978, see also McFadden, 1977) recently discussed least-squares techniques for making estimates of this common direction. Halls first found poles to the remagnetization circles as outlined above, and then repeated the procedure using the poles from all of the specimens. The pole to the final plane was considered to be the best estimate for the direction of the magnetic component common to all samples. Of course, both free and anchored demagnetization planes may be used in place of the remagnetization circles for this type of analysis, thereby increasing the amount of available data.

The final distribution of poles in Halls' analysis cluster about a great circle on the unit sphere. Individually, each pole indicates one direction where the remanence does not lie, but taken as a group they reveal by elimination the common direction. Although not discussed by Halls, these data constitute an equatorial or girdle distribution of the type studied and applied to geological problems by Bingham (1964, 1974) and Watson (1960, 1965, 1966). As noted by Onstott (1978; and in preparation), Bingham's general distribution is applicable to both bimodal and girdle paleomagnetic data and may be used to calculate directional concentration parameters and 95% confidence angles about each eigenvector, including the remanence direction.

Although it is not the purpose of this paper to weigh the relative merits between Fisher's (1953) and Bingham's (1964, 1974) distributions, Bingham statistics will be used here primarily for 3 reasons: Firstly, it is antipodally symmetric. If L is an observed unit direction of a line or a pole to a plane, $(-L)$ contributes identically to Bingham's analysis. This is necessary because the pole to a demagnetization plane could be chosen in either direction. Also, it was not generally recognized in 1953 that the

Earth's magnetic field had two polarity states (normal and reversed), each with roughly equal probability. Fisher consequently developed a monopolar distribution for analyzing paleomagnetic data. Secondly, Bingham's distribution equally handles bimodal, girdle, and asymmetric girdle data, and is not constrained to circular symmetry. Finally, Bingham statistics are based on a matrix similar to that used in principal component analysis (eq. 1). Onstott (1978, and in preparation) gives a definitive evaluation of this topic in relation to paleomagnetic studies.

6. ESTIMATION OF REMANENCE DIRECTIONS USING BOTH LINES AND PLANES.

As noted earlier, a demagnetization line is an estimate of the direction of a discrete magnetic component, while a pole to a demagnetization plane is an estimate of where the two magnetic components defining it do not lie. Paleomagnetic studies may identify some specimens with discrete lines while others have secondary overprints and yield only planes. For computing an average remanence direction, one first would like to use data from specimens which had good demagnetization lines, and then further constrain the result by including demagnetization planes from all samples which did not yield good lines. In this manner the best data from each specimen would contribute to the average magnetic direction reported. The proper technique should treat demagnetization lines and Hoffman-Day directions equally and allow for the calculation of error parameters about the final direction. Two methods of attacking this problem are outlined below, although both are as yet incomplete.

6.1 Method 1.

Viewed as points, data from demagnetization lines and Hoffman-Day directions relating to a common component will group in one or two clusters (normal and reversed polarity) at opposite ends of the unit sphere. On this same sphere, poles to demagnetization planes will distribute themselves about an equator roughly 90° from these bipolar clusters. To find a best estimate of the remanence direction, we want to pass a line through the center of the sphere so that it comes out at either end as close as possible to the bipolar clusters, while being as distant as possible from the poles along the equator. In essence, poles to demagnetization planes are 'repelling' the line while the bipolar points 'attract' it. The mathematical problem becomes that of jointly minimizing the sum of squared deviations from the line to the bipolar data while maximizing the squared deviations from the equatorial points. Maximizing the deviations for the poles, however, is equivalent to minimizing their

deviations from a plane which passes through the origin perpendicular to the line (Schomaker, et al., 1958). Therefore, let D_i , $i = 1, I$ be the distance from the i th demagnetization line or Hoffman-Day direction on the unit sphere to the line through the center, and let D_j , $j = 1, J$ be the corresponding distance from one of the poles from demagnetization planes to the perpendicular plane. The best remanence direction is then that which minimizes the sum:

$$S = \sum D_i^2 + \sum D_j^2 \quad (4)$$

Using the method of Lagrange multipliers, one eventually finds the matrix relation:

$$(H_j - H_i - \lambda I)M = 0 \quad (5)$$

where H_j and H_i are the respective matrices of the sums of squares and products for the plane and line data (like eq. (1) with $U = [0,0,0]$), M is a unit vector, and λ is the Lagrange multiplier. The minimum eigenvector from the combined matrix, $H' = H_j - H_i$, is now the best least-squares estimate of the joint remanence direction. This procedure may be equally used to find the best direction for a sample with many specimens or to combine data from many samples.

Although this procedure will isolate the best remanence direction with both lines and planes, the corresponding problem of calculating the directional (Bingham-type) concentration parameters and error-ovals has not yet fully been solved. The intermediate eigenvector of H' will parallel the largest (least-precise) axis of the confidence oval, and it is known that the eigenvalues of H' sum to $J-I$. Further work on this problem is continuing.

6.2 Method 2.

If through some simple transformation the equatorial and bipolar groups of points on the unit sphere could be mapped into a common spherical distribution, the data would be homogeneous and manageable. Again, this transformation should treat demagnetization lines and Hoffman-Day directions equally and

allow for the calculation of error parameters. One such transformation is to replace each direction in the bipolar cluster with two others which are mutually orthogonal to it. These two new points then lie on the equatorial distribution along with poles from the demagnetization planes, and the final distribution may be handled like those for the intersecting demagnetization planes discussed above. Fortunately, it has been shown that any two orthogonal directions considered as a pair in this manner contribute equally to each term in the matrix of sums and squares and products (eq. (1) with $U = [0,0,0]$). Thus, an arbitrary pair of mutually orthogonal points perpendicular to a line or Hoffman-Day direction may be used in the analysis without loss of generality, and Bingham statistics may be calculated from the final matrix. An unresolved question, however, is the manner in which the two new equatorial points should be weighted in the analysis compared to poles from demagnetization planes. The one-specimen, one-point rule commonly used in Fisherian statistics suggests that the two new directions each be given half weight since they arise from only one specimen. Eigenvalues from the joint matrix will then sum to the total number of samples, N . Therefore, in lieu of a more rigorous derivation, half weights will be used in the following examples.

7. EXAMPLES

7.1 Non-intersecting demagnetization planes: an example from Siberia

For this first example, 126 separately oriented samples were collected from a locality called Zerinsky Mys south of Yakutsk on the Lena River in Siberia (U.S.S.R.). Oriented cores 2.5 cm in diameter were collected with a hand-held drill at regular intervals from 55 meters of red to grey, flat-lying limestone. Strata were paleontologically dated as lower Tommotian to Atdabanian (both lower Cambrian). One specimen from each core was thermally demagnetized using standard techniques in 9 steps up to 650°C (NRM, 150, 250, 350, 450, 500, 530, 560, 610, 650). Of the pale-grey samples, 46 became unstable and gave irreproducible results after treatment above 560°C; for these, the unstable steps were omitted from the subsequent analysis as they clearly did not represent measurements of the natural magnetism. Presumably, their remanence was carried by magnetite and/or titanomagnetite with Curie temperatures near 580°C. The magnetization of these rocks will be described in more detail elsewhere (Kirschvink and Rozanov, in prep.).

The natural remanent magnetization (NRM) for most of the Siberian rocks was directed northerly with steep downward inclination, suggesting that most of it was recently acquired in the present magnetic field. Upon progressive demagnetization, 96 samples produced visually acceptable arcs on a stereonet and indicated the presence of a 2-polarity component of smaller magnitude and higher thermal stability. Only 3 specimens reached stable endpoints. The 2-component system present in 96 specimens therefore offers a good test for comparing various techniques which have been proposed for estimating the orientation of coplanar points along a demagnetization path.

As noted earlier, either of two antiparallel directions may be used to specify the direction for a pole to a demagnetization plane without affecting Bingham statistics. The direction in which the remanence moves upon demagnetization may have significance for polarity interpretation, however,

so it seems advantageous to consistently select one of the directions. In the example at hand, most arcs begin at steep, northerly directions and move upon demagnetization towards shallow NE or SW declinations, depending upon the polarity of the primary (more stable) component. For this and in the following examples, a right-handed convention has been used for selecting the pole direction (e.g., the pole most parallel to the vector cross-product, (low demag) X (high demag), represents the plane). Thus poles with SE declinations indicate arcs moving towards the NE, and NW declinations indicate arcs moving toward the SW.

In the present example, tectonic or other geologic processes have not acted to scatter one magnetic component relative to the other. This case is therefore distinctly different from those described by Halls (1976, 1978) where both discrete directions could be found by using converging circular paths. These are sub-parallel, non-converging remagnetization paths. In the converging case, the scatter of one component relative to the other will cause poles to demagnetization planes to distribute themselves about an equator on the unit sphere. Poles will still lie on an equator if neither component is scattered, however, but they will tend to fall in two clusters at opposite ends of the unit sphere. This is a girdle distribution with high circular asymmetry (Bingham, 1974), and as such resembles the bipolar cluster of line data. These clusters are perpendicular to both magnetic components; the principal eigenvector from the spherical least-squares calculation gives the best estimate of where neither magnetic component lies. Although this information would not tell the direction of the primary component, it locates a plane in which it must lie. The orientation of this plane may then be used to constrain the paleogeographic position of the continent involved.

Each of the five different methods discussed earlier were used to estimate the directions of poles to the 96 Siberian demagnetization planes. Stereographic equal-area projections on Fig. 4 give these directions in order of increasing complexity, going from free demagnetization planes (4A), anchored demagnetization

planes (4B), remagnetization circles (4C, Halls, 1976), difference vectors (4D), and to difference-vector paths (4E, Hoffman and Day, 1978). Table 1 lists the principal eigenvector for each set of data, along with the two Bingham concentration parameters and 95% angles of confidence about it. Visual inspection of Figs. 4A-E reveals that in each case the poles are distributed along a great circle which dips to the SE, with two somewhat dense clusters in the NW and SE. Values for K_2 in table 1 would be near 0 if the data were circularly distributed about the equator, thus the observed K_2 values indicate a moderate tendency for circular asymmetry. Similarly, directions for the principal eigenvector (u_1) found with each of the five methods do not vary significantly.

Closer examination, however, reveals that the direction of a pole to coplanar data from a single specimen may vary greatly depending upon which technique is used. For example, the bipolar cluster for the remagnetization circles on Fig. 4C is more distinct than those on any of the other diagrams; apparently removing the intensity data in this case slightly improves resolution of the primary component. A more direct test is to compare the angular difference between estimates of the poles for each specimen with the general coplanarity of the data. The histogram on Fig. 5A shows the distribution of specimens vs. their coplanarity measured by the maximum angle of deviation (M.A.D., eq. 3 above). The Siberian samples clearly have a wide spectrum of coplanarity; 37 specimens have deviation angles of less than 15° , while 21 have angles greater than 25° . Intuitively, one expects highly coplanar data to yield essentially the same pole direction regardless of the technique used, while marginally coplanar data would yield wildly different directions. Scatter diagrams 5B-E test this prediction by comparing the maximum angle of deviation (M.A.D.) against the angular distance between poles. Each point on these diagrams represent one specimen; points to the left represent highly coplanar data while points to the right do not. If every technique gave

identical results, all points on these scatter diagrams would lie close to the horizontal axis. Figs. 5B and D show that there is good directional agreement between free planes, anchored planes, and difference vectors for M.A.D. values below 15° . Above this, however, angular differences of nearly 90° are found. The comparison between free planes, remagnetization circles, and difference-vector paths (Figs. 5C and E) is far worse - angular differences of 45° or more occur from specimens with small M.A.D. values. Below values of 15° , remagnetization circles fare slightly better than difference-vector paths; 8 of 37 circles change their direction by more than 10° whereas 14 of 37 difference-vector paths change. Truncation of the intensity is probably responsible for these differences when compared to free demagnetization planes. A similar comparison between remagnetization circles and difference-vector paths (Fig. 5F) shows poor directional agreement.

In summary, difference vectors, free and anchored demagnetization planes yield similar poles to coplanar demagnetization data for M.A.D. values below 15° ; remagnetization circles enhance the effect of weak components while difference-vector paths increase the degree of scatter. Because pole directions were not highly reproducible for the 59 samples with M.A.D. values larger than 15° , they were removed and the calculations for table 1 repeated as shown. In each case the value of K2 became more negative indicating a greater tendency for bipolar clustering. Again, the direction for u_1 is not sensitive to the particular technique used. For the remaining 37 samples, Bingham's (1974) asymptotic ovals of 95% confidence around the principal eigenvector are shown on each diagram of Fig. 4. With 95% confidence, the primary remanence direction should lie somewhere within the equatorial bands drawn on Fig. 4C. Given the additional geologic information that there are diverse Archeocyathid bioherms with abundant carbonate sediments, a low-latitude of deposition ($\leq 30^{\circ}$) may be inferred. The shaded area on Fig. 4C therefore gives the most probable locus of the paleomagnetic axial dipole direction for Lower Cambrian

time on the Siberian platform. This is as far as the analysis of the primary magnetic component may go without invoking additional assumptions concerning the nature of the blocking temperature distribution for each component.

7.2 Joint line and plane analysis: the Série lie de vin, Morocco

In the previous example, remagnetization parallel to the present local magnetic field obscured the primary magnetic component of most specimens. A better example to illustrate the joint analysis of demagnetization lines and planes comes from the basal units of the Late Precambrian Série lie de vin, exposed near the village of Tiout in the Anti-Atlas mountains, Morocco. A total of 28, 2.5 cm. diameter oriented core samples were collected at regular intervals through 70 meters of strata. One specimen from each core was subsequently thermally demagnetized in a manner similar to that described for the Siberian samples above. Typical demagnetization paths are shown on the vector diagrams in Fig. 6. Above 300-350°C, most specimens decay linearly towards the origin and indicate the presence of a single characteristic magnetic component. A principal component search of the data set along the lines of Fig. 1 located 21 specimens, each of which had 4 or more collinear points and M.A.D. values of less than 10°. Of these, 19 included the origin. Although the remaining 7 specimens did not have demagnetization lines, all had demagnetization planes with 5 or more points and M.A.D. values below 10°. Corresponding directions for lines and planes of best least-squares fit, anchored to the origin where appropriate, are shown in Fig. 7A. As expected, poles to the 7 demagnetization planes lie on a great circle roughly 90° from the antipodal cluster of linear directions.

Table 1 and Fig. 7 separately list and plot the remanence directions and associated Bingham statistics for the colinear and coplanar data, as well as for the equatorially transformed lines (section 6.2 above) and joint estimates (methods 1 and 2, sections 6.1, and 6.2 above). After tilt

correction, the remanence direction as estimated separately from lines and planes differs by 8° , it is therefore worthwhile to test the hypothesis that the directions are not statistically different before the data are used in a joint calculation. At the present time, the best available method for doing this is to transform the antipodal line directions into a girdle distribution according to section 6.2 above, and then use Watson's (1965) directional test. Written in terms of the eigenvalues, large values of the F-ratio statistic,

$$F(2, L + P - 4) = \frac{\frac{L + P - 4}{2} \cdot \frac{\lambda_{\min, \text{combined}} - \lambda_{\min, \text{planes}} - \lambda_{\min, \text{T.Lines}}}{\lambda_{\min, \text{planes}} + \lambda_{\min, \text{T.lines}}}}{(6)}$$

indicate that the directions are distinct. For this example with 21 lines and 7 planes, $F_{2,24} = 0.278$, implying that the directions cannot be distinguished at the 99% confidence level and they may be combined. Note, however, that the equatorial transformation of the linear data alone produced a 7° shift in remanence direction which may have contributed to the apparent significance of this test. The combined remanence direction found with method 2 also reflects this bias and is closer to the transformed line direction than the original. Method 1 yields the preferred remanence direction which lies between that computed for isolated lines and planes, but error parameters cannot, as yet, be calculated for it.

Conclusions

1. Principal component analysis may be used to find and estimate the directions of lines and planes of best least-squares fit along a demagnetization path of a paleomagnetic specimen. These lines and planes are based on all of the available data, not just on the two end points of a line segment (like vector subtraction) or on directions devoid of intensity (like remagnetization circles and difference vector paths).

2. Because eigenvalues from the principal component analysis are the variance (σ^2) around the mean along each principal axis, they may be used to indicate the relative collinearity or coplanarity of a set of points. The Maximum Angular Deviation (M.A.D.) calculated from the variance provides a paleomagnetic precision index based only on the geometry of the data set.

3. Demagnetization planes may be used in place of difference-vector paths for locating Hoffman-Day directions, thereby increasing the accuracy by avoiding the vector subtraction and intensity truncation steps.

4. Demagnetization planes are useful in paleomagnetic studies because their poles give an estimate of a direction in which two magnetic components do not lie. This additional information may be used along with directions from demagnetization lines to estimate an average direction for a component of magnetic remanence.

Acknowledgements

R. B. Hargraves, T. C. Onstott, M. E. Purucker, S. L. Gillett, and an anonymous referee gave extremely useful and informative advice during the development of this paper. I thank D. P. Elston of the U.S.G.S. and M. C. Steiner of CalTech for use of their paleomagnetic laboratories, as well as G. Choubert and A. Yu. Rozanov who made it possible for me to collect samples in Morocco and Siberia, respectively. The computer program for calculating Bingham's directional concentration parameters was written and cheerfully loaned to me by T. C. Onstott; a program for doing all other things described in this paper is available upon request. This work was supported by NSF grant EAR78-03204, and constitutes part of my PhD thesis from the Department of Geological and Geophysical Sciences, Princeton University.

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Table 1 - Comparison of planar techniques for non-intersecting Siberian demagnetization planes.

All Planes:	N	u_1		K1	K2	ov.az.	$\alpha_{95\min}$	$\alpha_{95\max}$
		Dec	Inc					
Free Planes	96	330.9	-16.3	- 9.3	- 2.4	103.8	4.1	9.7
Anchored Planes	96	335.1	-16.9	- 8.6	- 2.7	103.4	4.3	8.7
Remagnetization Circles	96	338.2	-17.7	- 8.2	- 3.6	103.5	4.2	7.0
Difference Vectors	96	329.8	-15.2	-10.3	- 1.8	101.9	4.0	12.6
Difference Vector Paths	96	336.1	-16.6	-10.1	- 2.1	99.7	4.0	10.6
<u>Planes with M.A.D. < 15°:</u>								
Free Planes	37	328.8	-16.9	- 8.7	- 3.6	95.1	6.6	11.1
Anchored Planes	37	329.6	-17.3	- 8.6	- 3.6	94.4	6.6	11.0
Remagnetization Circles	37	329.9	-16.8	- 8.2	- 4.1	92.4	6.7	10.1
Difference Vectors	37	327.5	-16.6	- 8.8	- 3.8	96.1	6.5	10.8
Difference Vector paths	37	327.3	-14.3	- 9.9	- 3.1	98.3	6.1	12.6

N - Number of specimens contributing demagnetization planes to the analysis

u_1 - (Dec, Inc) Direction of the principal eigenvector. For this analysis, u_1 estimates the direction in which neither magnetic component lies.

ov. az. - The spherical angle measured at u_1 between vertical and u_2 . Directions for the two eigenvectors unspecified in this table (u_2 and u_3) may be found using the direction of u_1 and the ov. az.

K1, K2 - Bingham's concentration parameters (from density $d^{-1}[K1, K2] \exp[K1(u_3 \cdot L)^2 + K2(u_2 \cdot L)^2]$, where L is the random population variable, and d^{-1} is a normalizing constant).

$\alpha_{95\min}$, $\alpha_{95\max}$ - Bingham's (1974) approximate angles of 95% confidence. The direction of $\alpha_{95\max}$ always parallels the intermediate eigenvector (u_2).

Table 2 - Combined line and plane directions for the Serie lie de vin,
 Anti- Atlas Mountains, Morocco. Results enclosed with brackets ()
 have not been corrected for local tilt of the strata.

	N	Dec	Inc	K1	K2	ov.az.	$\alpha_{95\min}$	$\alpha_{95\max}$
Lines	(21	168.1	-38.7	-26.25	-10.03	118.3	4.4	7.3)
	21	161.8	-20.2	-17.36	-14.44	105.4	5.4	6.0
Lines, Transformed	(21	175.9	-39.4	-11.10	- 0.41	127.7	9.4	10.7)
	21	169.4	-21.2	- 8.82	- 0.32	113.7	10.9	12.1
Planes	(7	175.8	-36.1	-70.41	- 0.82	42.8	5.8	7.2)
	7	167.6	-14.5	-28.46	- 0.94	35.2	9.2	11.9
Method 1 combined	(28	169.5	-38.2			48.8		
	28	162.9	-19.3			47.3		
Method 2 combined	(28	176.1	-38.5	-13.16	- 0.05	116.1	7.6	7.9)
	28	169.3	-19.7	-10.05	- 0.10	70.0	8.9	9.2

N - Number of lines or planes in each analysis.

Dec, Inc - Direction of average remanence. -

K1, K2 - Bingham concentration parameters (see table 1).

ov.az. - The spherical angle measured at the remanence direction between
 vertical and the direction of $\alpha_{95\max}$.

$\alpha_{95\min}$, $\alpha_{95\max}$ - Bingham's (1974) approximate angles of 95% confidence. The
 direction of $\alpha_{95\max}$ always parallels the intermediate eigenvector.

Fig. 1 A flow chart for locating collinear and coplanar pieces of the demagnetization path. The N data points are numbered sequentially starting with the NRM, and a search begins by setting the J index on the origin (0,0,0) and the index I on the N-1st point. These 3 points in the first window between I and J are checked for linearity. If they do not fall on a line, the window is moved further down the demagnetization path and again tested. When 3 collinear points are found, neighboring points are added until the boundaries of the straight segment are located. The window is then repositioned and the search process repeated until no further linearity remains. The "I, J linear?" test is positive if the M.A.D. for the points I through J is less than a given value. Data points which lie on a plane may be found by starting with a similar 4-point search window.

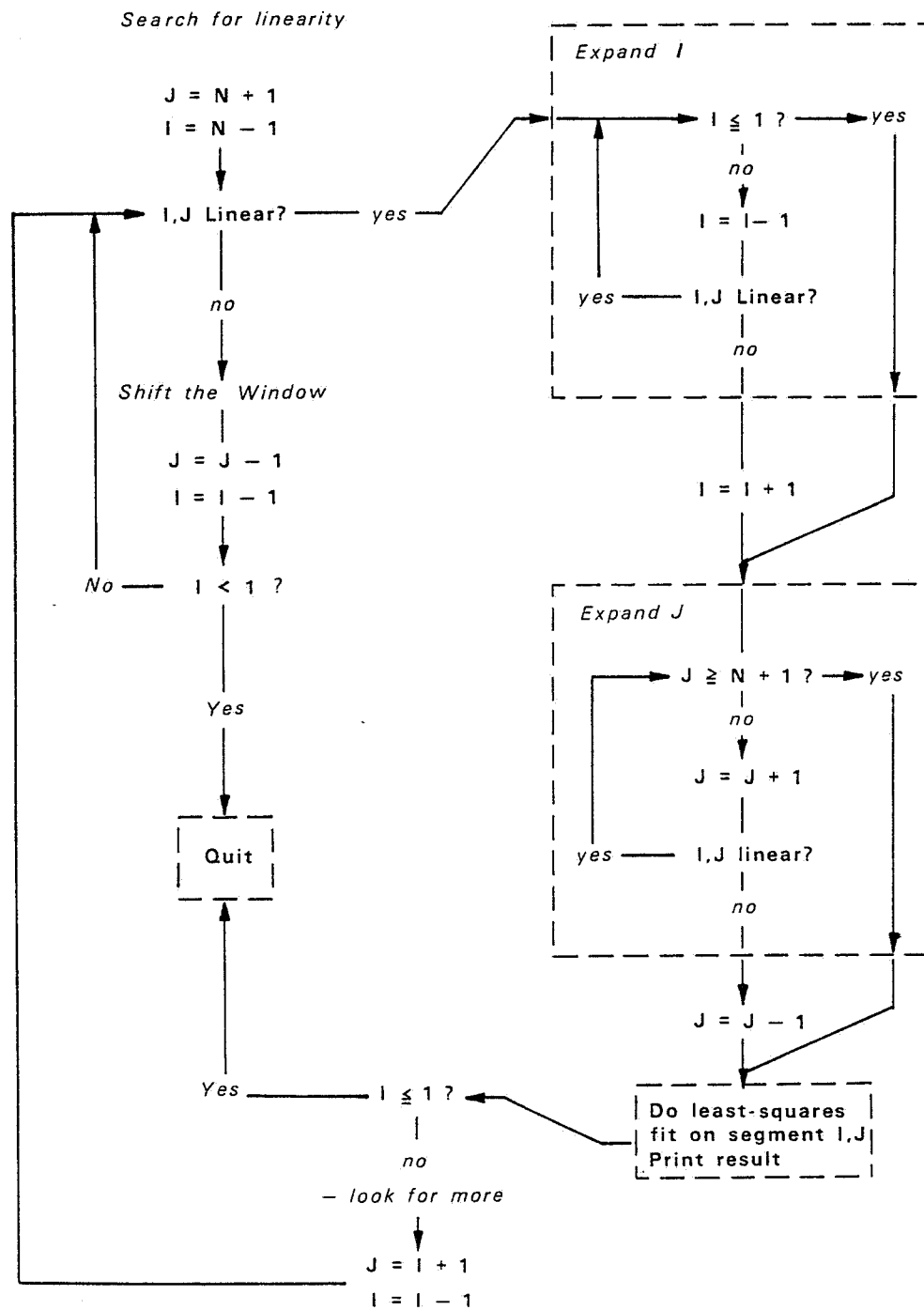


Fig. 2. Five methods for estimating the direction of a pole to a set of coplanar points, NRM through Origin. Upper diagram: Free demagnetization planes pass through the centroid ($\oplus$), while anchored planes are fixed to the origin. Remagnetization circles are fit to unit directions on the sphere and again include the origin. Lower diagram: Difference vectors form another group of points to which a plane constrained to include the origin may be fit. Finally, a plane may be fit to the difference vector paths.

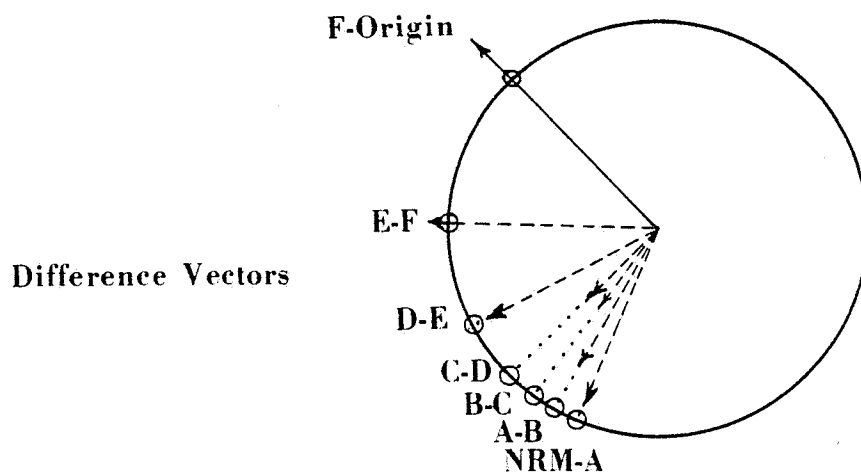
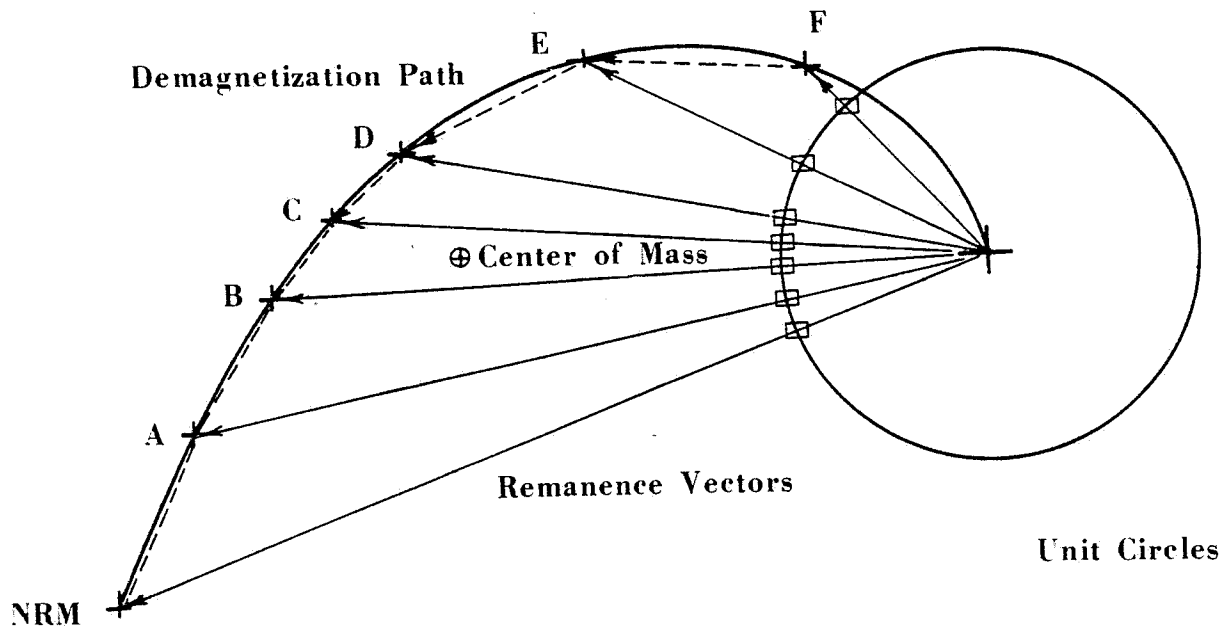
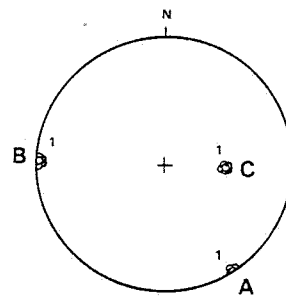
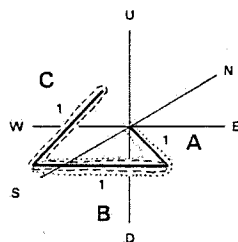
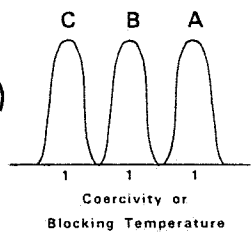
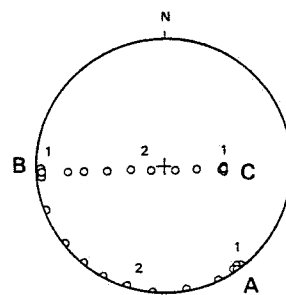
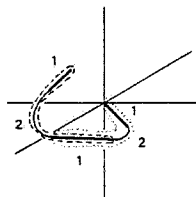
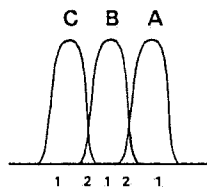


Fig. 3. Hoffman-Day directions. In each figure, the letters A, B, and C each refer to a separate magnetic component. Small numerals give the number of different magnetic directions being removed simultaneously due to overlap of the coercivity or blocking temperature spectra. Two demagnetization planes are shown in the central figure of each row; the [B,C] plane is enveloped with a dashed line, and dotted line surrounds the points on the [A,B] plane. Dark lines in this figure show linear regions. The stereonet shows the direction of vectors removed sequentially by demagnetization (the difference vector paths), open symbols are on the upper hemisphere. (A) - No overlap in components, all lines and planes may be found. (B) - Slight overlap between neighbors, lines and planes are still present. (C) - Component B completely overlaps A and C, with a slight A-C overlap. No linear part of B remains, but the direction may be found as discussed in the text. (D) - B overlaps completely with A and C, no linear segments remain but the B direction may still be recovered. Figure adapted from Hoffman and Day (1978).

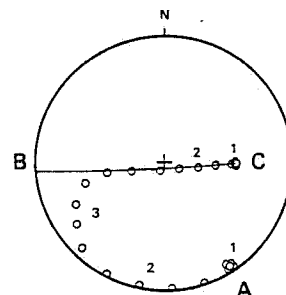
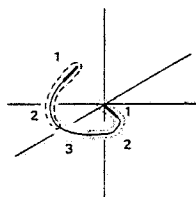
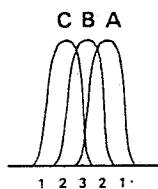
(A)



(B)



(C)



(D)

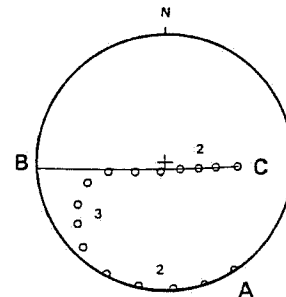
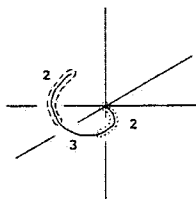
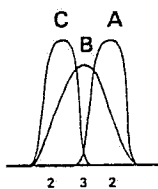
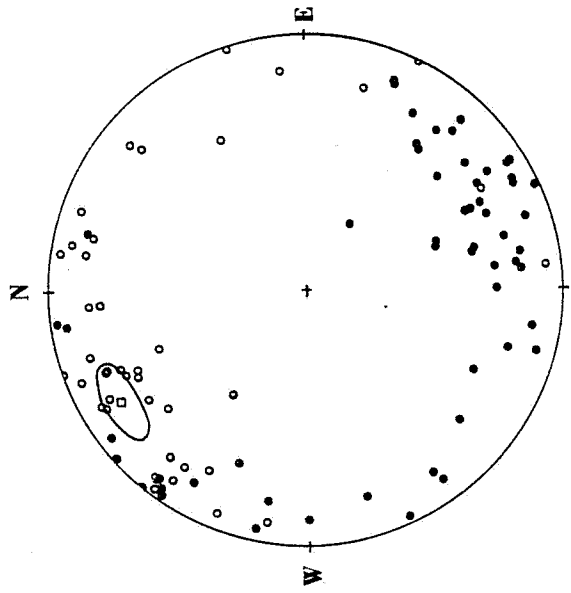
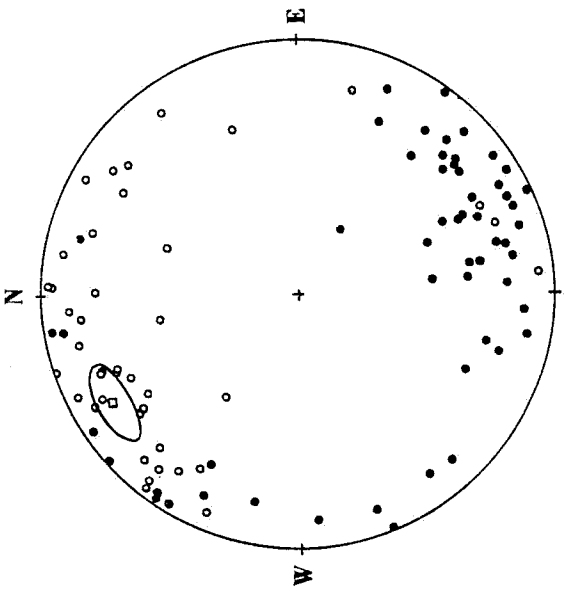


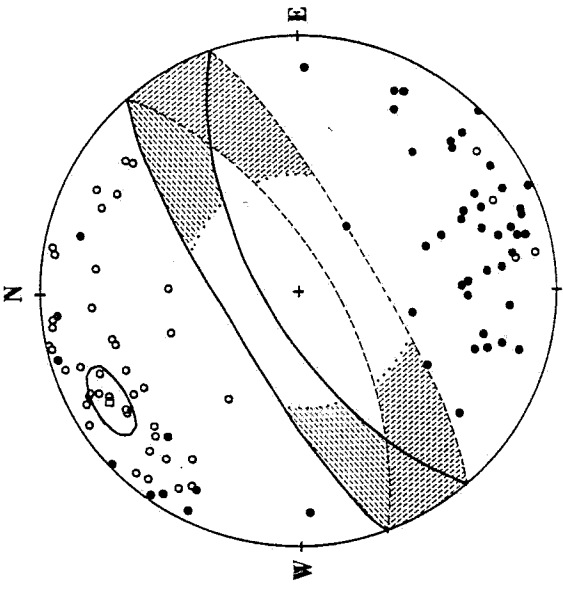
Fig. 4. Comparison of pole directions for coplanar demagnetization data obtained with each of the five methods outlined on Fig. 2. Original magnetic data come from 96 Siberian samples collected at Zerinsky Mys. Open symbols indicate directions on the upper hemisphere (negative inclination). Open squares show the direction of the principal eigenvectors from the restricted data set ($M.A.D. < 15^{\circ}$) along with their ovals of 95% confidence. Fig. 4C also gives the 95% boundaries along a girdle distribution in which both the primary and secondary magnetic directions lie; the shaded portion of the girdle corresponds to paleoinclinations below 30° North or South.



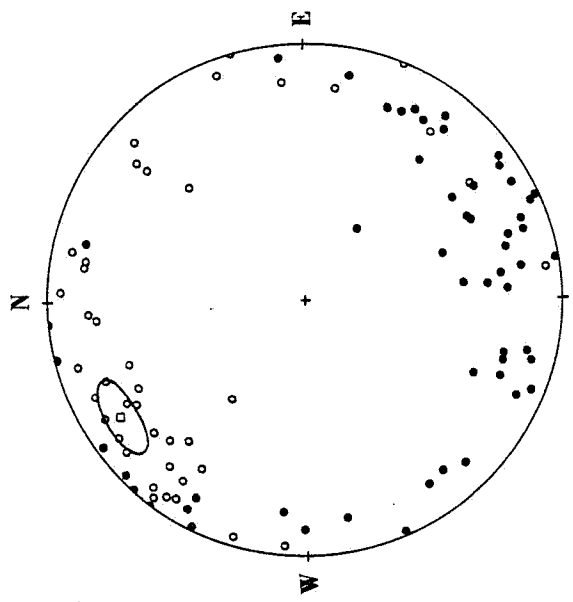
A. Free Planes



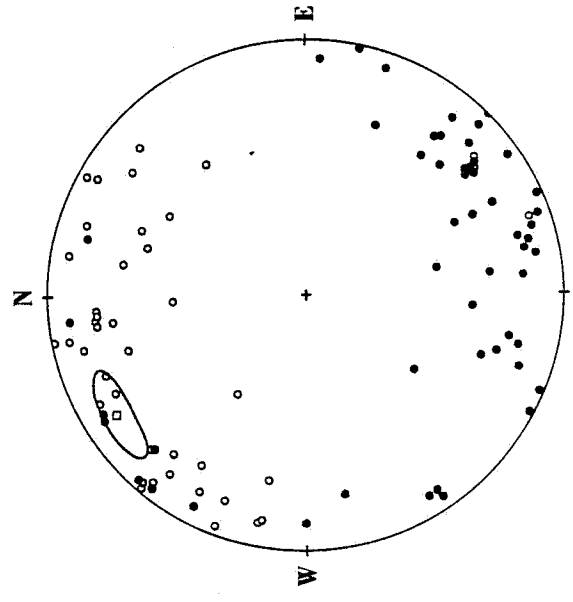
B. Anchored Planes



C. Remagnetization Circles



D. Difference Vectors



E. Difference Vector Paths

Fig. 5. Comparison of planar techniques. (A) - Distribution of M.A.D. values for 96 Siberian samples. (B) to (F) - Scatter diagrams showing agreement of pole directions vs. coplanarity of points.

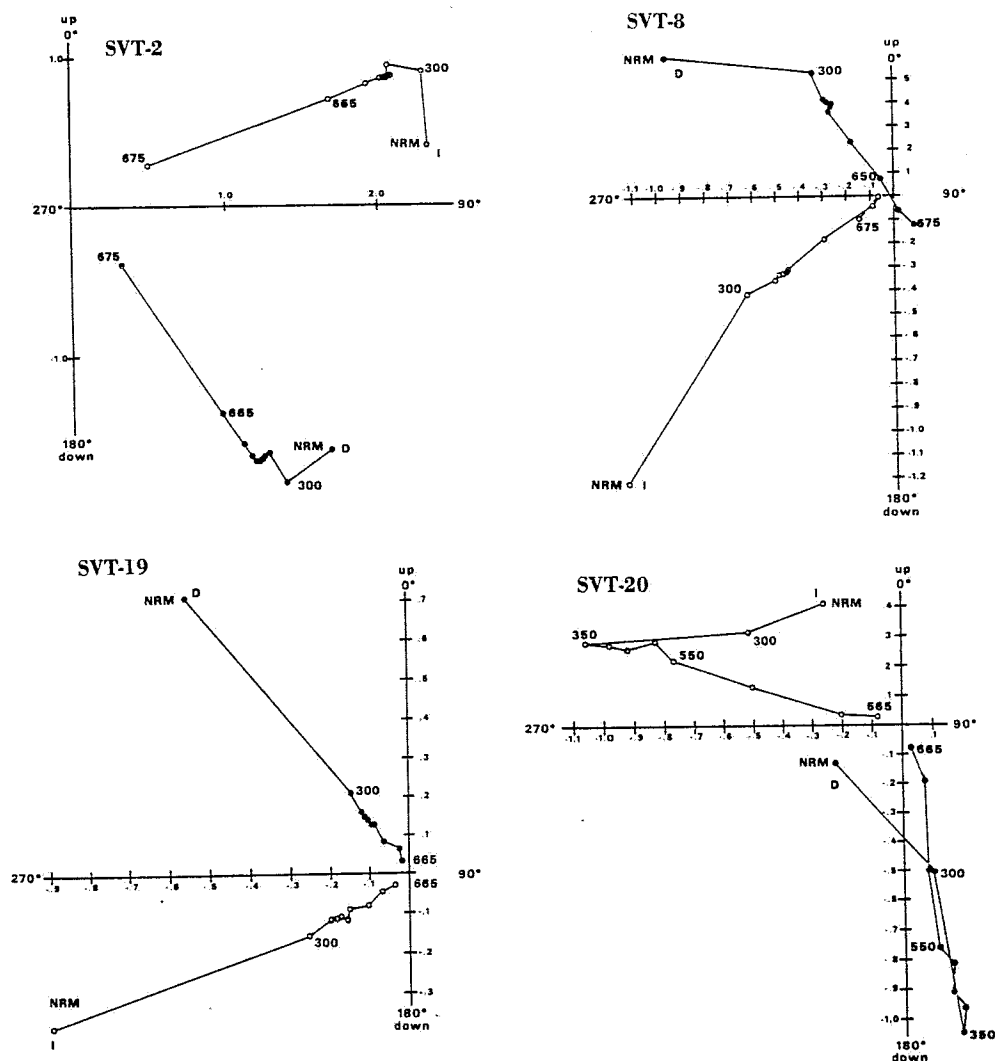
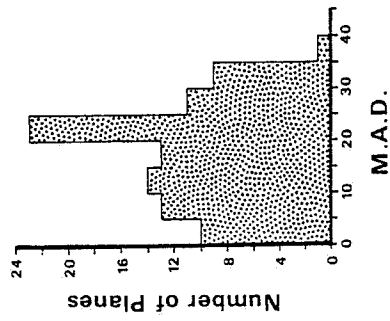
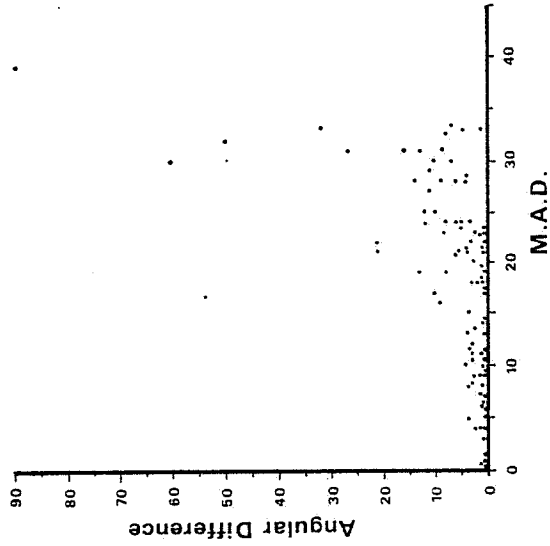


Fig. 6. Vector demagnetization diagrams. Numbers along the axes refer to the magnetic intensity in units of 10^{-6} emu/g (or Am^2/kg). Paths labeled D (declination) show the horizontal projection into the bedding plane of the demagnetization path, and those labeled I (inclination) plot the vertical component against the horizontal. Although it is not strictly an orthogonal projection, an inclination curve plotted in this fashion directly shows the inclination and intensity of the remanence vector at each demagnetization point. Occasionally, a line will plot on this curve as part of a hyperbola. The sampling locality, Tiout, is at 30.35°N , 8.67°W .

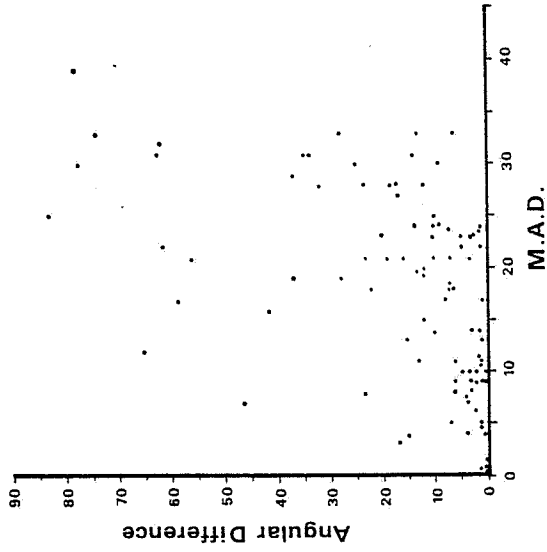
A. M.A.D. Distribution



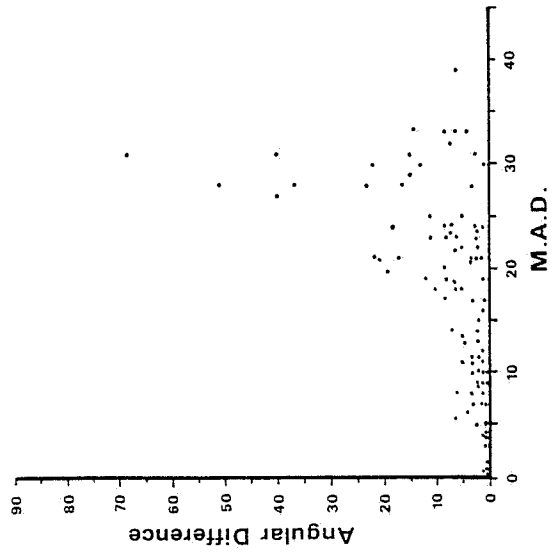
B. Free vs. Anchored Planes



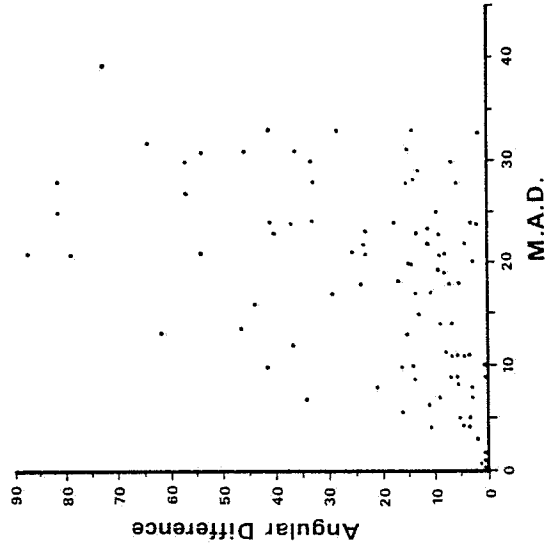
C. Free Planes vs. Remag. Circles



D. Free Planes vs. Difference Vectors



E. Free Planes vs. Difference Vector Paths



F. Remag. Circles vs. Difference Vector Paths

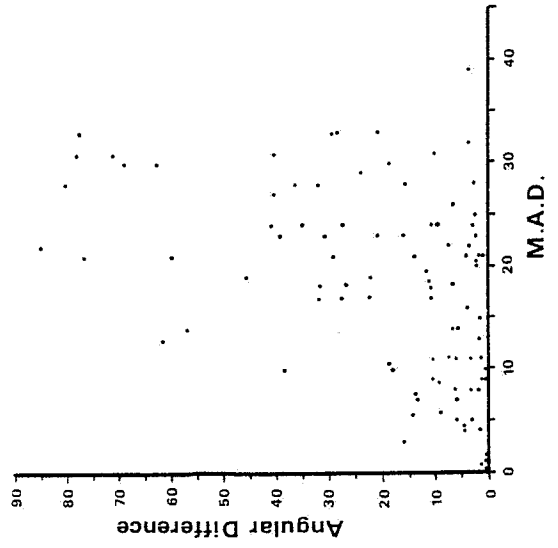
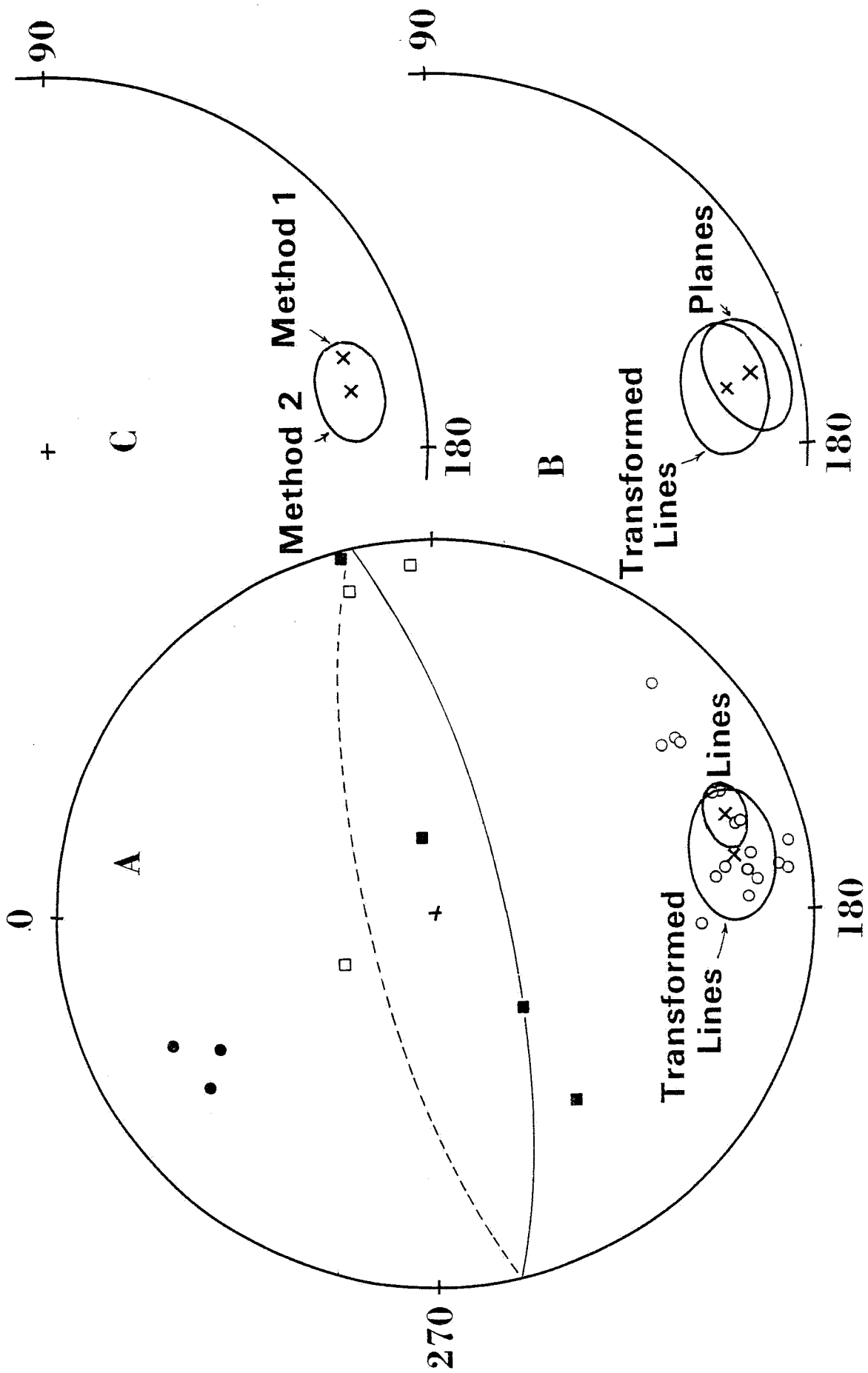


Fig. 7. Results from the Serie lie de Vin, Morocco. (A) - Circles are the directions for 21 demagnetization lines with M.A.D. values below 10° . Squares show similar directions to the poles for the remaining 7 demagnetization planes. Ovals plotted on A, B, and C are the average directions and Bingham 95% confidence ovals as listed on Table 2.



Remagnetized Late Precambrian to lower Cambrian Sediments on the Burin
Peninsula of Newfoundland: A Late Cambrian - Early Ordovician Paleomagnetic
Pole for the Avalon Microcontinent

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ABSTRACT

Paleomagnetic evidence suggests that Late Precambrian to Early Cambrian greenish sediments on the southern tip of the Burin Peninsula, eastern Newfoundland, were remagnetized during regional deformation between Middle Cambrian and mid-Ordovician time. A paleomagnetic pole computed from this secondary direction lies between mid-Cambrian and lower-Ordovician results on the North American apparent polar wander curve, but may equally be compared with Ordovician data from the British Isles after closure of the Atlantic.

INTRODUCTION AND PHILOSOPHY

Late Precambrian and lower Cambrian rocks on the southern portion of the Burin peninsula, south-eastern Newfoundland comprise an apparently continuous sedimentary sequence which locally records the first appearance of shelly life. Fletcher (this volume) describes the stratigraphy, geologic setting, and faunas which have recently been discovered on this portion of the Avalon zone. Because this sequence potentially could serve as a stratigraphic reference for positioning the Precambrian-Cambrian boundary, we undertook a paleomagnetic study. If primary magnetic components are present, the magnetic stratigraphy could aid in intercontinental correlation as well as place constraints on the position of eastern Newfoundland in lower Cambrian time. Secondary magnetic directions, if present, might be related to the subsequent geologic history of the rocks.

In this report, we present preliminary results from paleomagnetic sampling at 4 localities on the southern portion of the Burin Peninsula (Fig. 1). Work on these sediments and on additional samples from other localities is continuing.

SAMPLE LOCALITIES, COLLECTION, AND LABORATORY PROCEDURES

Greenish claystone and occasional limestone units at each of the 4 localities shown on Fig. 1 are free from weathering and continuously exposed in sea cliffs. Core samples 2.4 cm in diameter were collected with a portable gasoline-powered drill similar to that described by Doell and Cox (1967); orientations in the field were measured with a Brunton Compass and, when possible, a sun compass. The location of each sample in the stratigraphic sequence was accurately noted and plotted on the stratigraphic columns given by Fletcher (in preparation). In order to maximize the stratigraphic resolution and reduce effects of secular variation, cores were drilled at even intervals of one to several meters; the thickest sequence sampled was at Fortune Head (260 m, 198 samples), followed by Drunkard's Point (40 m, 35 samples, North Fortune Cove (30 m, 35 samples), and Duck Point (23 m, 31 samples, all on Fig. 1).

In the laboratory, cores were soaked briefly in concentrated HCl and rinsed ultrasonically in tap water to remove any metallic contamination from the drilling process. They were then sliced into an average of two or three standard cylinders 2 cm long, each of which weighed about 30g. Directions and intensities of remanent magnetic vectors were made with a computerized, 2-axis superconducting rock magnetometer with an effective sensitivity of 5×10^{-9} emu/g ($= 5 \times 10^{-9}$ Am²/Kg; Goree and Fuller 1976). Progressive demagnetization experiments were conducted using: (1) liquid nitrogen for low-temperature cycling, (2) a Schoenstedt thermal demagnetizer, and (3) a single-axis, 400 Hz Schoenstedt alternating field (AF) coil. All magnetic measurements and demagnetization experiments were performed inside a Mu-metal shielded room with a typical residual magnetic field of less than 50 nT ($\ln T = 1\gamma$); additional Mu-metal shields reduced this level to less than 1 nT during measurements, low temperature cycling, and AF demagnetization, and to below 15 nT during thermal demagnetization in air. Samples were not exposed to the ambient

magnetic field (55,000 nT) at any time during the series of demagnetization experiments. The data set generated in this study was searched for colinear and coplanar directions using techniques described elsewhere (Kirschvink, in review; Hoffman and Day 1978). Average directions and associated statistics for the NRM and demagnetized samples are given in Table 1.

STABILITY OF NRM

As shown on Fig. 2, NRM directions obtained from the greenish sediments have a moderate amount of scatter but show only a minor streak towards the present local field direction. Magnetic intensities averaged near $2 \times 10^{-7} \text{ Am}^2/\text{Kg}$, well above background. After correction for stratigraphic tilt, magnetic directions generally dip south-southeasterly; at North Fortune Cove, however, tilt correction has the opposite effect and will be further discussed later.

Progressive thermal demagnetization experiments were performed on one specimen from each core sample from Drunkard's point. As shown on the vector diagrams (Fig. 3, top), the intensity of the NRM decays smoothly with temperature accompanied by a small deflection away from the direction of the present field. Above 590°C , directions and intensities of the magnetism notably begin to fluctuate. This magnetic viscosity implies that the natural remanence has been destroyed, probably accompanied by chemical alterations. Seven samples acquired this viscosity at an early stage of demagnetization and were of no use in the subsequent analysis. There were no additional thermally discrete magnetic components isolated during demagnetization, nor were there any equatorial (girdle) distributions found among the high-temperature demagnetization planes.

A total of nine specimens from North Fortune Cove and Fortune Head have been subjected to progressive AF demagnetization up to peak fields of 60 mT (60 oe). Again, the directions remained stable and decayed smoothly in intensity towards the origin (Fig. 3, bottom).

MAGNETIC MINERALOGY

Three magnetic minerals which could account for the observed remanence are: (1) magnetite or titanomagnetite, (2) hematite, and (3) pyrrhotite. Hematite is unlikely to be the source because it generally has higher AF and thermal stability and, if pigment were present, would give a reddish hue to the rocks. Pyrrhotite is a possibility because the presence of pyrite (replacing skeletal material of gastropods) suggests excess sulfur. The Neel temperature of pyrotite ($\sim 305^{\circ}\text{C}$) is less than that of magnetite (585°C), so the remanence at higher temperatures is probably due to magnetite. A low temperature cycle produced a small decrease in remanent intensity in samples from North Fortune cove, which further supports the presence of at least some multi-domain magnetite (Levi and Merrill 1978). The magnetite may have been produced inorganically, although at this time we cannot rule out biogenic precipitation of single-domain magnetite by bacteria (Blakemore 1975; Frankel, et. al. 1979; Kirschvink and Lowenstam, in press).

AGE OF THE MAGNETIC REMANENCE

Fig. 4 is a stereographic plot of the average stable demagnetized vectors; arrows connecting the points indicate directions before and after correction for local tilt of the beds. Although they have not yet been demagnetized, the NRM directions from Duck Point have been included for comparison. Error parameters have not been computed for the two sites at Fortune Head and North Fortune cove due to the small number of specimens demagnetized.

As noted earlier, tectonic correction moves results from Fortune Head, Drunkard's Point and Duck Points to S-SE directions with shallow downwards inclination. At the same time the result from North Fortune Cove starts near there and is moved away. A simple Fisherian fold test comparing the grouping of these sites before and after tilt correction is not significant at the 95% confidence level. If we make the ad-hoc assumption that the North

Fortune locality was magnetized in a reversed field after deformation, switch this direction and run the test accordingly, the significance level is greater than 99%. This result is compatible with the interpretation that 3 of the sites were magnetized before deformation and that the fourth (North Fortune Cove) was almost completely folded at or after that time. Because deformation in this area was not penecontemporaneous with deposition, these sediments must have been remagnetized; hence they are of no use for magnetic polarity stratigraphy. The magnetic overprint direction seems to have been gained during and on cooling after the low-grade regional metamorphism and development of large-scale folds; on this basis it can be bracketed by the stratigraphy on the Burin Peninsula between Middle Cambrian and Carboniferous (Strong et. al., 1976), Kennedy (1976) describes the major Paleozoic deformation and metamorphism in Newfoundland's Eastern crystalline belt to the west of the Burin Peninsula as pre-middle Ordovician; hence it seems likely that the secondary remanence was gained between mid-Cambrian and mid-Ordovician time.

PALEOMAGNETISM

Paleogeographic Remanence Directions

In paleomagnetic studies of sedimentary rocks, it is usually assumed that strata were originally horizontal when they gained their primary magnetization. Before an apparent geomagnetic pole position is computed, remanence vectors from tectonically deformed areas are therefore mathematically rotated above horizontal axes back to correspond to their original orientation. If the remanence has failed a direct geologic test of its age (fold, conglomerate, or unconformity) one can only assume that no tectonic events have acted within the area subsequent to magnetization and compute the pole position from the uncorrected data. The age of the magnetism is then most uncertain. In the case at hand, however, deformation appears to have occurred before, after, and perhaps during

remagnetization; therefore one must be cautious when applying tectonic corrections to the data. A pole computed from the best cluster of site directions from the Burin is probably close to the geographic direction of the time of deformation, but it seems necessary to check this by computing a pole which, in some fashion, is independent of the particular tilt corrections used.

Statistical techniques which have recently been introduced in paleomagnetic studies can be extended to solve this problem. On Fig. 4, arrows along the dotted lines indicate the change of direction produced by correcting the magnetic vectors for tilt. If the vectors are (1) roughly perpendicular to the horizontal strike line of the beds or (2) the magnitude of the tilt rotation is small, the path connecting the magnetic directions before and after tilt correction will approximate a great circle, although a small segment in case 2. Simple deformation involving nonplunging folds (i.e., horizontal fold axes) will not rotate the strata about a vertical axis. Under these conditions, remagnetization close to the time of deformation implies that the remanence will be gained at some point along these circular paths. The point at which these circles converge provides an estimate of the ancient remanence direction. Methods exist for estimating this best direction from converging circles, for calculating Bingham concentration parameters, and for constructing 95% error ovals about the mean (Halls, 1976; Bingham, 1964, 1974; Watson, 1965, 1966; Onstott, 1978 and in preparation). The first step in this analysis is to find normal vectors perpendicular to the plane of each circular path (Hargraves, 1959); in this case they are given by the cross-product of the two vectors which define the circle. The direction perpendicular (pole) to this final circle gives the best estimate of the convergence point or remanence direction, and the Bingham distribution can be used to calculate error parameters around it. A paleomagnetic apparent pole position computed from this final direction is then free from the bedding correction problem and may be compared with other data on a polar wander curve.

Conditions necessary to use the above technique are met by the data from the Burin Peninsula. At Fortune and Duck point, the fold axes run N-NE whereas the remanence is generally S-SE; Drunkard's Point has only a minor tilt correction. Directions which are perpendicular to the circles defined by the remanence vectors before and after tilt correction, given by their cross-product $B \times A$, are listed in table II. The best estimate of the remanence direction from these circles and the 95% confidence oval are plotted on Fig. 4 and correspond to a provisional Late Cambrian to Early Ordovician paleomagnetic pole for the Avalon microcontinent at 16.8°S , 336.3°E . This result has a highly elongate error oval due to the gradual intersection of the circles on Fig. 4; hence it is a conservative estimate of the true direction. For comparison, the 95% oval computed from the best-grouped directions is also shown and may be regarded as a more liberal guess. The angular separation between the average directions for these two methods is only 1.5° ; hence our use of the best grouped directions seems justified.

Apparent Polar Wander (APW) path for the Avalon Microcontinent

The Avalon zone of Newfoundland is attached to the North American plate today, but may have been part of one or more microcontinents in the past. Because geologic evidence is against large-scale rotations of Newfoundland (Deutsch and Rao 1977), the APW path for the Avalon zone should match that from North America for most of Phanerozoic time. The point at which the APW paths join marks the time at which most relative motions became small. Key paleomagnetic pole positions for reference to mainland North America are plotted on Fig. 5 along with the two 95% ovals for the secondary direction from the Burin Peninsula. Reference poles of Ordovician and younger are those

accepted by Morel and Irving (1977), while Cambrian paleomagnetic results are those selected by Gillett and Van Alstine (in press) and Elston and Bressler (1977), and new data from Watts and VanDerVoo (1979). Paleomagnetic poles calculated from the Burin Peninsula data fall between late Cambrian and early Ordovician directions on the North American APW curve. Fig. 6 shows this same comparison with Ordovician data from Great Britain, after correcting them for the post-Ordovician opening of the Atlantic Ocean.

DISCUSSION

Although paleomagnetic results reported here from the Burin Peninsula agree reasonably well with the North American APW curve, it is by no means conclusive evidence that the Avalon microcontinent shared the same plate motions as North America. The interpretation of these data is complicated because the age of deformation and associated remagnetization and metamorphism on the Burin Peninsula is only loosely bracketed between mid-Cambrian and mid-Ordovician time. If the true age is early Upper Cambrian, plate tectonic models which invoke little relative motion between the Avalon microcontinent and mainland North America are favored (see the discussion by Schenk, 1978). Small intervening oceans could be closed or opened without disturbing this agreement. On the other hand, a true age of post Early Ordovician for the magnetization does not agree as well with the North American APW curve, but does agree with Ordovician poles from the British Isles if one corrects for Mesozoic and Tertiary opening of the Atlantic (Fig. 6). This latter interpretation would imply that the Avalon microcontinent moved along with the British Isles during sinistral transcurrent faulting as suggested by Morris (1976).

One way of testing the first hypothesis (attachment of the Avalon zone to North America in the Upper Cambrian) is to see whether or not the remagnetization event influenced western Newfoundland. If the deformation and low-grade

metamorphism were a response to the start of continental collision between the Avalon zone and North America (i.e., closure of the proto-Atlantic), both sides might show remagnetization effects from the same event. Of the data from Newfoundland reviewed by Deutsch and Rao (1977), directions from the lower Cambrian Bradore sandstone (western Newfoundland) are similar to those found in this study. In their report on the Bradore, Rao and Deutsch (1976) preferred to interpret the 680°C magnetic component as primary but left open the possibility that it was a secondary remagnetization. Data from their two localities (Canada Bay and St. John Bay) are listed in table II before and after correction for tilt. Note that directions from St. John Bay after correction are closer to those from Canada bay before correction, suggesting that the Bradore magnetization was secondarily gained during regional deformation as was the magnetization of our samples from the Burin Peninsula. The true Bradore remanence direction can therefore be found by using the same technique developed above to find the conservative estimate of the Burin direction, except that error parameters cannot be calculated with data from only two localities. Estimated in this fashion, the average pole position from the Bradore differs by only 0.6° from that of the secondary overprint on the Burin Peninsula (Table III). This may be only a coincidence; but if taken at face value it suggests that the first hypothesis described above is correct and that the Avalon microcontinent has been close to and moving with North America at least since Late Cambrian time.

On the other hand, lower Ordovician sediments on the Avalon platform to the East of the Burin Peninsula were deformed along with the Cambrian rocks. If deformation were synchronous across the Avalon microcontinent, it would imply that the remagnetization event was similarly post-early Ordovician and the paleomagnetic comparison with Great Britain is correct.

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Table 1. Preliminary paleomagnetic results from late Precambrian and lower Cambrian sediments of the Burin Peninsula, Newfoundland.
Numbers enclosed in brackets have not been corrected for tilt.

Locality & Location	Treatment	N	$\bar{D}$	$\bar{I}$	K1	K2	$\alpha_{\min}$	$\alpha_{\max}$	ov. az.
Drunkard's Pt. 46.92°N/304.49°E	NRM	35	(124.3	60.3	- 6.8	- 4.7	10.6	13.3	113.5)
			125.9	50.8	- 7.4	- 4.2	10.2	14.4	120.6
	650°C*	28	(139.6	53.6	- 7.7	- 5.7	10.9	13.1	105.5)
			138.6	43.9	- 8.4	- 7.1	10.2	11.2	199.0
Duck Pt. 46.9°N/304.50°E	NRM	31	(62.6	78.9	-15.4	-10.5	6.7	8.2	147.7)
			151.2	22.4	-11.7	- 8.2	7.9	9.6	104.2
North Fortune Cove 47.09°N/304.18°E	NRM	35	(158.2	54.0	- 6.1	- 4.8	11.4	13.2	4.9)
			313.3	30.8	- 6.9	- 4.8	10.5	12.9	154.2
	-196°C**	35	(156.9	51.0	- 8.9	- 4.1	9.2	14.4	177.1)
			313.3	34.0	- 8.5	- 4.6	9.3	13.2	4.7
Fortune Point 47.08°N/304.14°E	60 mT AF*	3	(153.9	37.0	-	-	-	-	-)
			312.6	48.9	-	-	-	-	-
	NRM	198	(299.3	72.9	-15.0	-11.7	2.7	3.0	56.0)
			163.7	47.8	-16.1	- 6.2	2.6	4.4	150.9
	60 mT AF*	6	(246.2	86.6	-	-	-	-	-)
			150.3	39.9	-	-	-	-	-

N - Number of samples, one specimen per sample reported.

$\bar{D}$, $\bar{I}$ - Average declination and inclination of remanence estimated by spherical least-squares.

K1, K2 - Bingham concentration parameters. K1 is a measure of the clustering along the inertial axis of greatest precision, K2 is the same measure at right angles to it. $K1 \sim K2 < 0$ represent a mono- or bipolar distribution, whereas $K1 \ll K2 \lesssim 0$ indicate the data are clustered along a great circle.

$\alpha_{\min}$, $\alpha_{\max}$ - Half angles of 95% confidence around the remanence direction, calculated from K1 and K2 according to Onstott (in review). $\alpha_{\max}$ is parallel to the intermediate eigenvector from the spherical least-squares calculation.

ov.az. - Azimuth of error oval: Spherical angle measured at the remanence direction between vertical and the direction of $\alpha_{\max}$.

* - Demagnetization lines, eigenvalue linearity > .975 (Kirschvink, in review).

** - Measured at room temperature after one low temperature cycle.

Table II Normal vectors to tilt correction circles.

Locality and Treatment	Before tilt Correction		After tilt Correction		Normal vectors (B x A)	
	D	I	D	I	D	I
Drunkard's Point, 650°C	139.6	53.6	138.6	43.9	226.2	-2.5
Duck Point NRM	62.6	78.9	151.2	22.4	245.8	11.1
North Fortune Cove 60 mT AF	153.9	37.0	312.6	48.9	55.5	11.0
Fortune Point 60 mT AF	246.2	86.6	150.3	39.9	52.8	8.8

Canada Bay (Bradore S.S. 680°C)	146.	18.	144.	4.	233.4	-7.8
St. John Bay (Bradore S.S. 680°C)	132.	25.	146.	30.	359.9	55.2

Table III Paleomagnetic poles from Newfoundland. Symbols are defined as on table I.

Rock Unit	Method	N	$\bar{D}$	$\bar{I}$	K1	K2	$\alpha_{\min}$	$\alpha_{\max}$	ov. az.	South Pole	
										lat.	long.
Burin Sediments (this study)	Best Group	4	148.9	36.0	-143.9	-22.1	4.2	10.6	20.3	-17.4	334.7
	Converging tilt circles	4	147.1	36.0	-80.9	-16.3	5.6	39.7	176.3	-16.8	336.3
Bradore Sandstone (Calculated from data in Rao & Deutsch, 1976).	Converging tilt circles	2	148.4	30.6	-	-	-	-	-	-17.1	335.2

Fig. 1 Location of the Burin Peninsula and sampling localities in Newfoundland

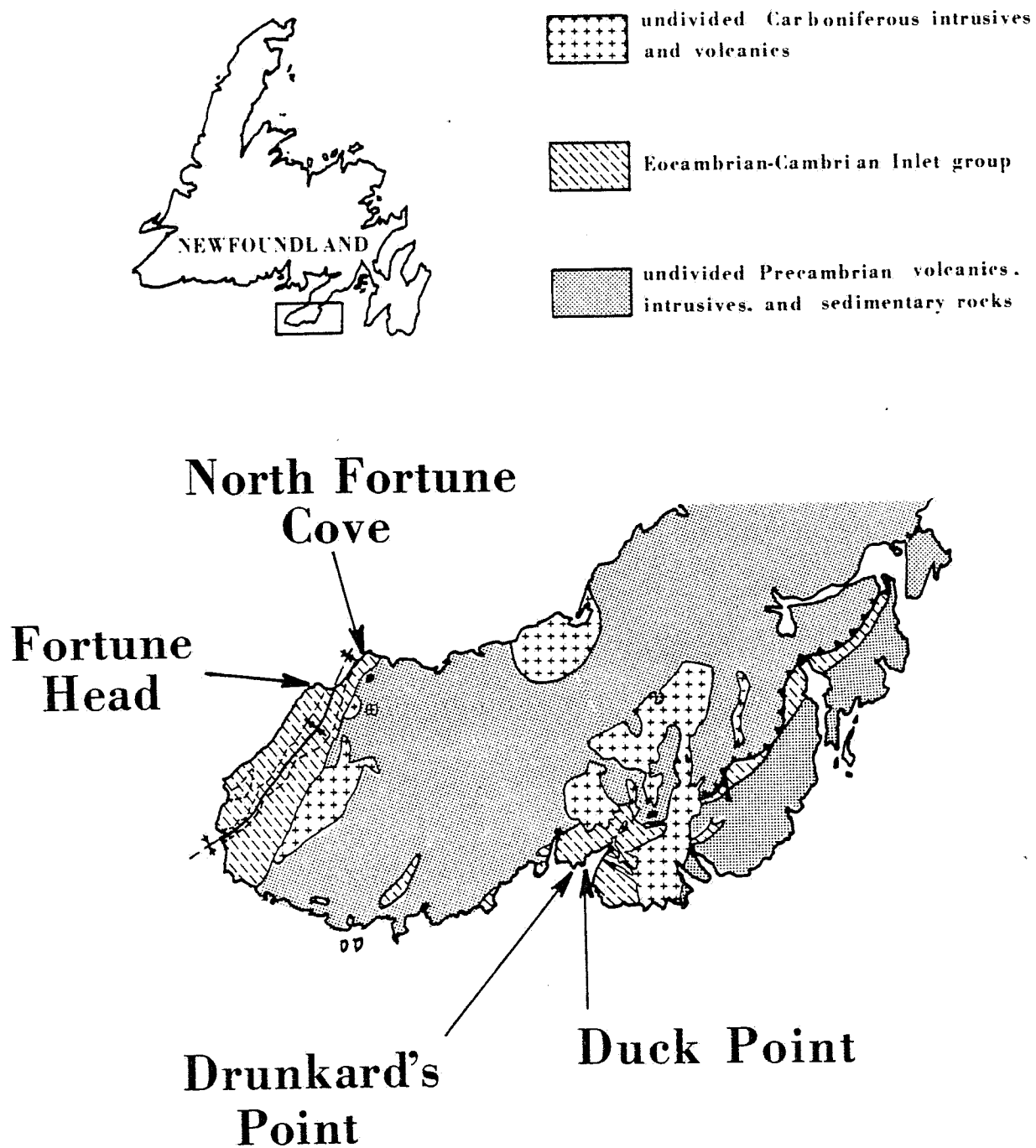
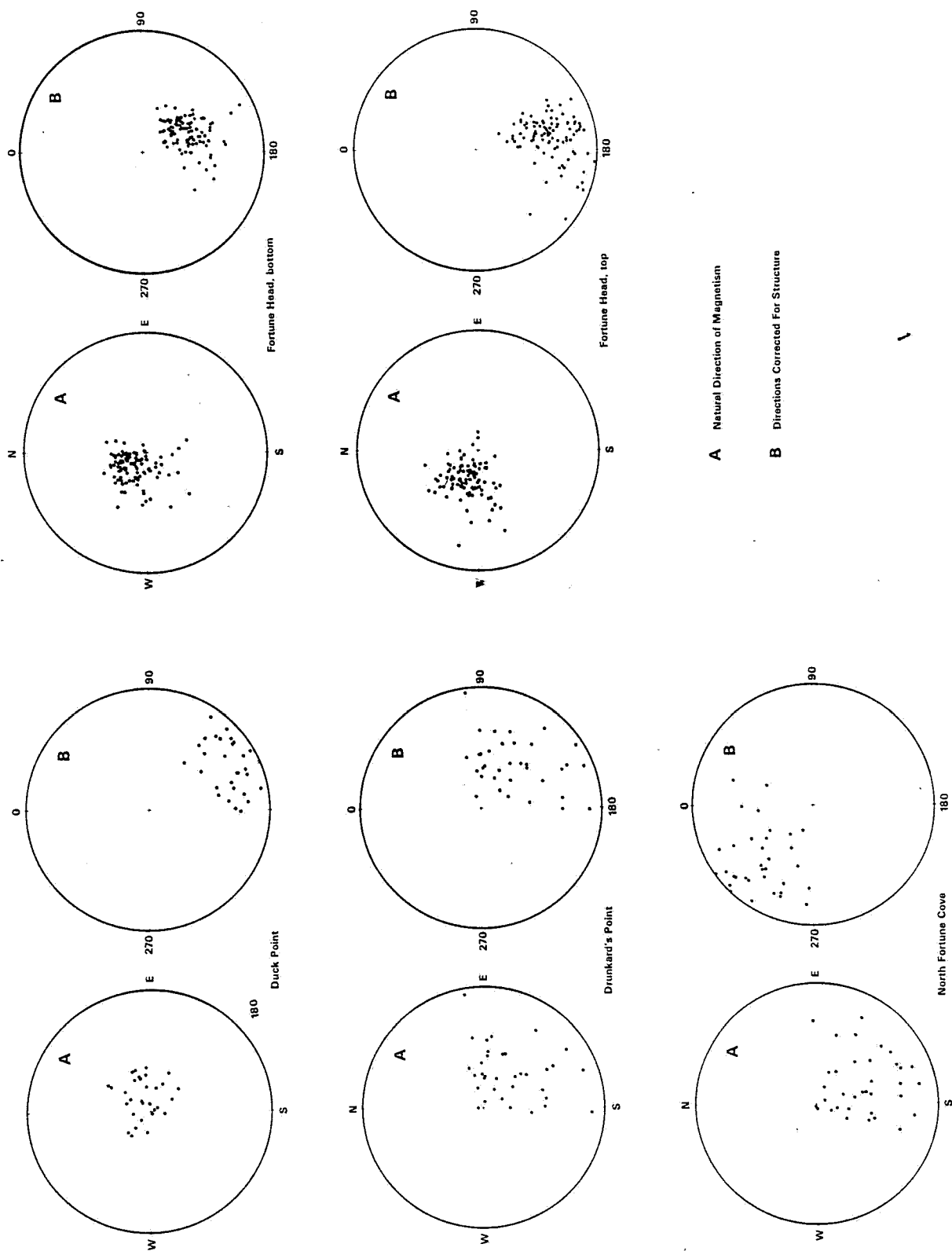


Fig. 2 Directions of Natural remanent magnetism before and after tilt correction.



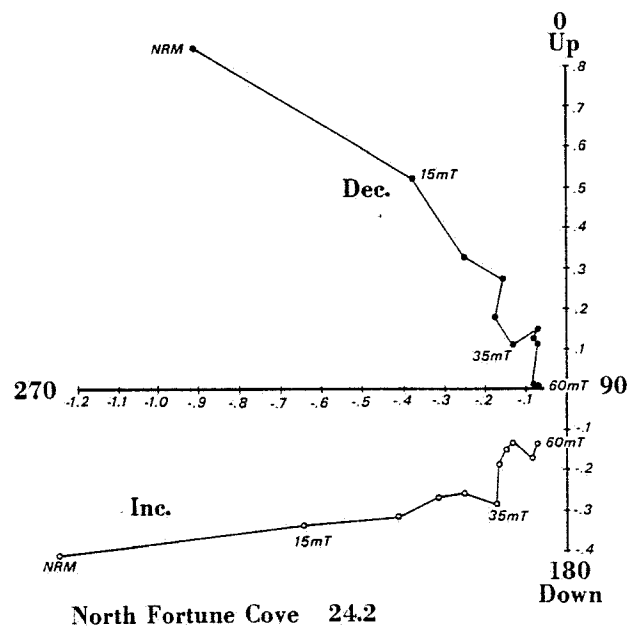
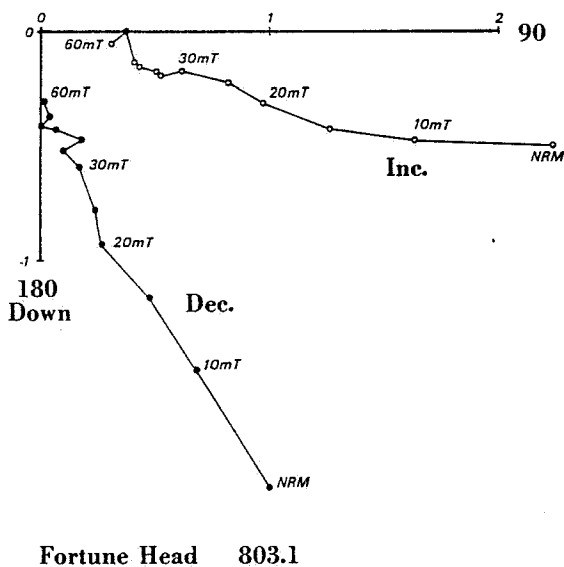
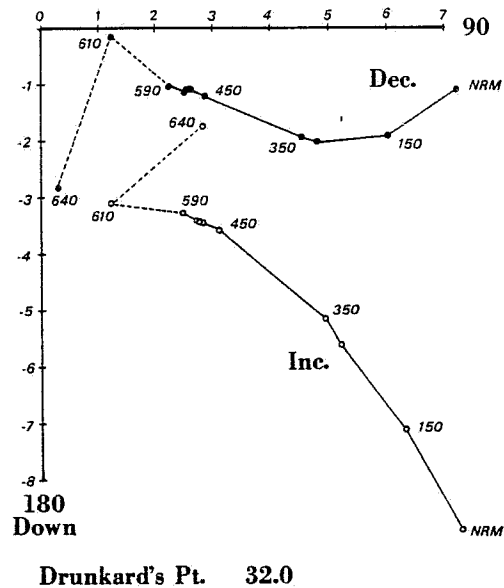
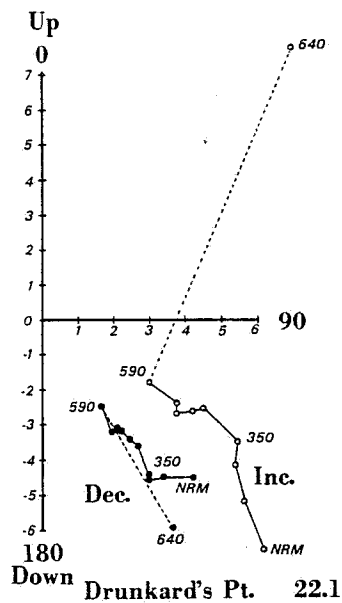


Fig. 3 Progressive demagnetization of green sediments on the Burin Peninsula. Numbers along the axes give specific magnetic intensity in units of 10^{-8} Am²/Kg (emu/gr). Curves labeled Dec. show the projection of the magnetic vector into the plane of the strata at each demagnetization step, while curves labeled Inc. give the inclination angle vs. intensity. Numbers along the bottom two graphs show peak AF demagnetizing fields in mT, while numbers on the top two graphs show the temperature in °C.

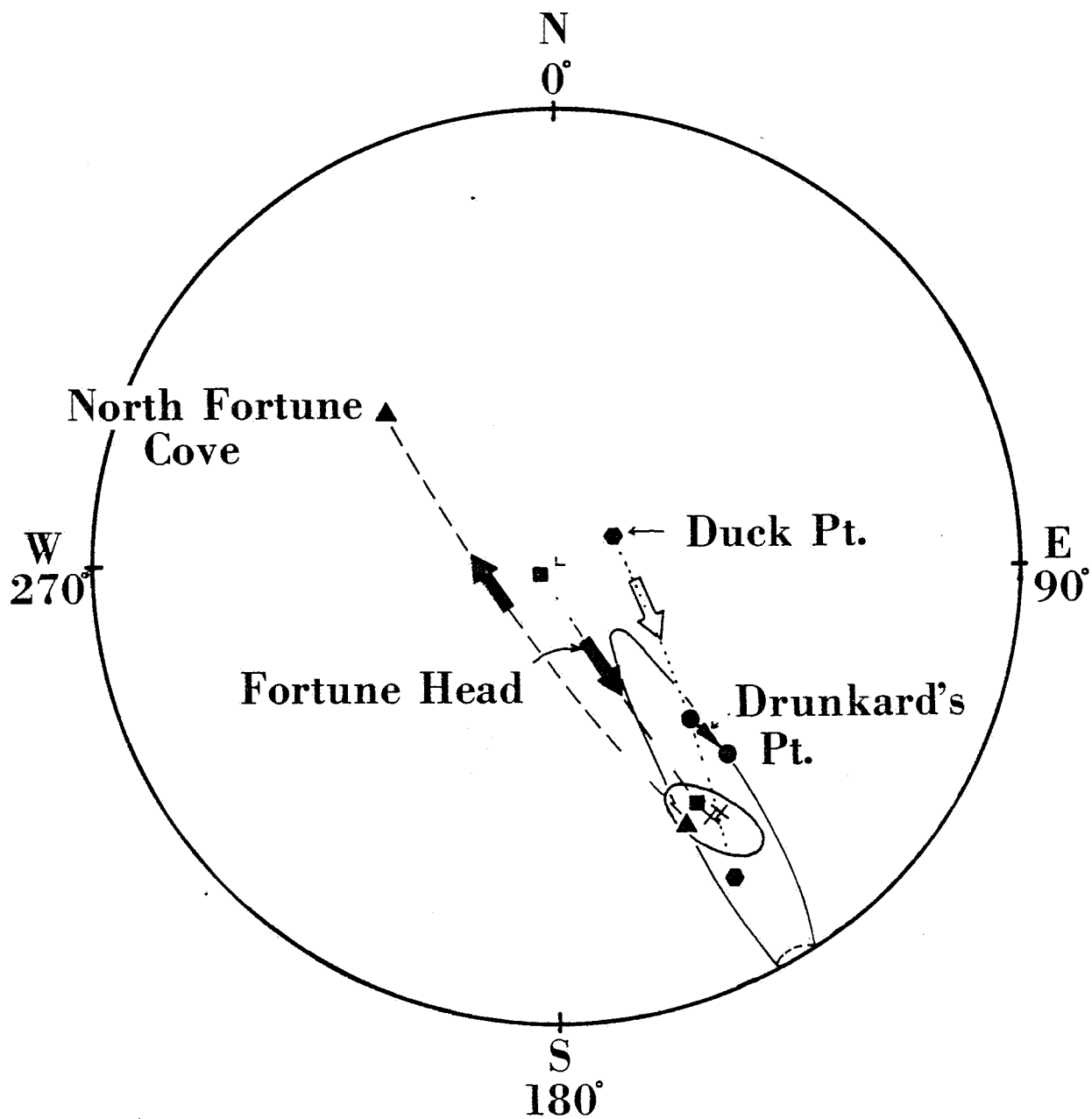


Fig. 4 Directions of average magnetic vectors before and after correction for structure. Arrows indicate the change produced by correcting for tilt. The small oval is the Bingham 95% confidence oval about the set of best-grouped directions, while the long oval shows the Bingham 95% oval about the center of intersection for the tilt circles listed in table II.

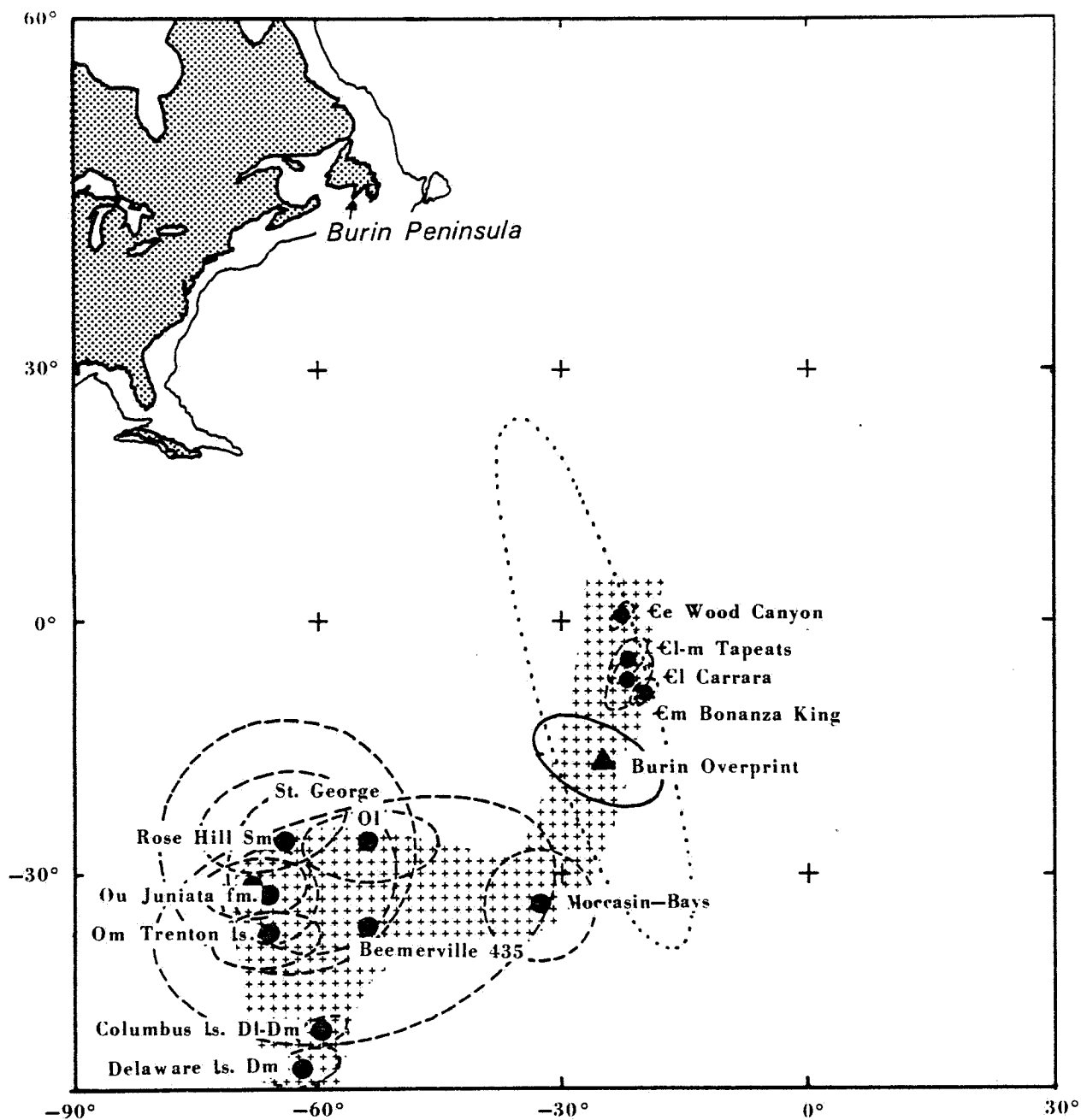


Fig. 5 North American apparent polar wander curve for the lower Paleozoic. Pole positions shown with dashed ovals are from mainland North America. The solid and dotted ovals are the VGP transforms of the two error circles shown on Fig. 4 from the Burin Peninsula.

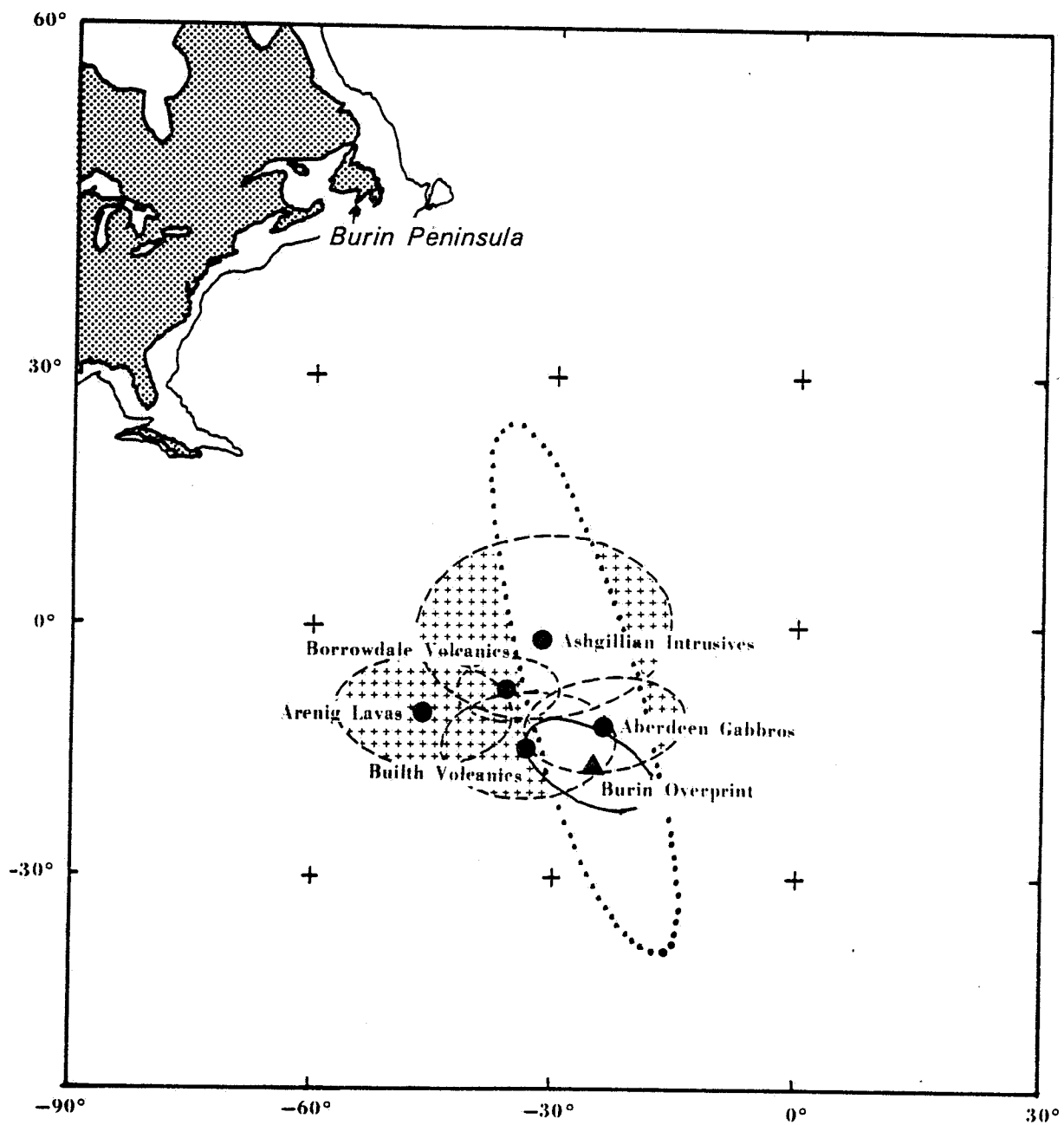


Fig. 6 Ordovician paleomagnetic poles from Great Britain, corrected for opening of the Atlantic (After Morris, 1976). Burin directions are as on Fig. 5.

MINERALIZATION AND MAGNETIZATION OF CHITON TEETH:
PALEOMAGNETIC, SEDIMENTOLOGIC, AND BIOLOGIC IMPLICATIONS
OF ORGANIC MAGNETITE

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ABSTRACT

Magnetite precipitation and tooth formation in chitons (Polyplacophora) proceeds through a biochemically-controlled reduction of the mineral ferrihydrite. Resulting crystals of single-domain magnetite are closely packed against one another and are typically near $0.1\ \mu\text{m}$ in diameter. The natural magnetization of these teeth is characterized by abnormally low stability to alternating field demagnetization (m.d.f. near 12 mT) but has no appreciable decay due to low-temperature cycling. Chitons may be responsible for natural magnetizations on the order of 10^{-6} Gauss in marine sediments, whereas mud bacteria could produce remanence near 10^{-8} Gauss in both marine and freshwater sediments.

1. INTRODUCTION

It has long been known that one group of Molluscs, the chitons (Polyplacophora), synthesize the ferromagnetic mineral magnetite [1]. Recent discoveries have extended this range to mud bacteria [2,3], honey bees [4], and to homing pigeons [5]. Magnetite possibly serves two biologic functions: in chitons, this mineral hardens the major lateral teeth for scraping surface and embedded algae from hard substrates in the sea. During this process, the magnetite is worn away and shed into the environment. The second function is related to navigation; mud bacteria, honey bees, and pigeons seem to use magnetite as a compass. Many other animals have been reported to be sensitive to local magnetic fields, and it seems likely that additional work on them will further widen the known spectrum of magnetotactic organisms.

Magnetite is also one of the two or three important minerals which give rise to stable fossil magnetism (paleomagnetism) in sedimentary rocks. As such, it is important to consider all potential sources from which it can be derived and will be ultimately preserved in the geologic record; biologic precipitates of magnetite have not been considered previously in this context. The mineralization and magnetization sequence of chiton teeth is considered first for the following reasons: Chitons are common in the sea and range from the intertidal to the abyssal zones. Their fossil record extends back to late Cambrian time. Teeth of living chitons are large enough to study their individual magnetic properties. Finally, the complete tooth mineralization process is sequentially displayed along the radula, enabling each stage of development to be studied.

We report here (1) new observations on the mineralization process of chiton teeth, (2) describe in detail their microarchitecture based on scanning electron micrographs, (3) show how the magnetic properties of the teeth are related to this construction, and (4) make a rough estimate of the potential contribution of chiton-derived magnetites to the magnetization of sediments. In the final section we discuss the significance of biogenic magnetites from arthropods, vertebrates, and bacteria.

2. MINERALIZATION SEQUENCE OF CHITON TEETH

Along the length of the radula or tongue plate in chitons, there are two parallel rows of mineralized major lateral teeth which are grouped in 30 to 70 tooth pairs. The most anteriorly located 5 to 7 pairs are functional, become abraded from scraping rocky substrates for food and are thereafter discarded (6). To replace them, the radula moves continuously forward, adding new teeth at its posterior end. Tooth maturation has been so far considered to pass through 3 developmental stages: unmineralized teeth, ferrihydrite deposition, and transformation of this ferric oxide mineral to magnetite (6). Additional mineral species have since been recognized in the teeth (7,8). We also have obtained new information on the modes and sequences of the mineralization process, in particular as they concern magnetite formation. This leads us to distinguish 4 developmental stages in tooth maturation, which differ somewhat in stages 3 and 4 between species from different families, as illustrated by Cryptochiton stelleri and Chiton tuberculatus in Figure 1. Their salient features from posterior to anterior are as follows:

Stage 1. This is the segment of the first 5 to 12 pairs of teeth, newly formed by the odontoblast cells at the posterior end of the radula. These teeth are colorless and consist of an organic framework which is unmineralized. (6)

Stage 2. The next 3 to 5 pairs of teeth are capped by a brown to reddish brown hydrous oxide material ($5 \text{ Fe}_2\text{O}_3 \cdot 9 \text{ H}_2\text{O}$) (6,9), which has been named ferrihydrite (10), and is known to constitute the micelle of the iron storage protein ferritin (6, 11). The amount of the ferrihydrite increases in an anterior direction within the consecutive tooth pairs. We have found that the ferrihydrite encloses lenticular to irregularly shaped bodies of magnetite in the most anteriorly located teeth.

Stage 3. On well cleaned radulae, the capping material of the next 25 to 29 pairs of teeth is surficially mineralized by magnetite. The onset of this stage is very conspicuous as it is marked by an abrupt change in color from the reddish brown teeth of the preceding phase to the black ones here. We discovered that after careful removal of the superior epithelia cells of the radular sac, which adhere tightly to the cap surfaces, these teeth are always thinly veneered by ferrihydrite. This material is poorly aggregated, becomes easily brushed off in the usual cleaning procedure of the radulae and seems to explain why it has escaped notice in the past. This ferrihydrite is clearly part of the tooth, not part of the adjacent tissue. The magnetite underlying this veneer increases in thickness anteriorly in the tooth pairs at this stage. The distribution and areal extent of the magnetite on the tooth cap surface is species defined, but without exception it is present at the cutting edge. From the start of biomineralization, i.e. in stage 2, parts of the anterior surface and the interior of the cap have an organic framework that remain unchanged and unmineralized until stage 4.

Stage 4. The feature common to the teeth of all species is: 1. continuing thickening of the magnetite fraction in the caps, and 2. the persistence of a surficial ferrihydrite veneer. The distinguishing feature of this stage is the infilling of the previously "vacant" parts of the tooth-caps by new mineral species. In Cryptochiton stelleri (Fig. 1) it is an amorphous hydrous ferric phosphate (8), a material similar in chemical composition to that in the dermal granules of the holothurian Molpédia intermedia (11). In Chiton tuberculatus (Fig. 1) 2 discrete minerals are added instead: lepidocrocite and francolite (7). These minerals occupy adjacent, sharply bounded separate areas in the tooth caps (7). The beginning of lepidocrocite deposition preceeds that of francolite by 5 tooth pairs and terminates shortly after the onset of francolite nucleation.

(Fig. 1). The buildup of francolite deposition extends over a series of about 20 tooth pairs. Its completion coincides with the cessation of ferrihydrite formation and magnetite accretion. This signals the termination of the biomineralization process of the teeth.

The anteriorly located 24 ± 2 pairs in C. stelleri and C. tuberculatus (Fig. 1) are now in mineralization terms fully mature, representing the reserve of functional teeth for the replacement of those shed after mechanical wear.

These data indicate that the magnetite added throughout the biomineralization of the teeth is always a transformation product of ferrihydrite. The most conclusive evidence is the first appearance and subsequent proliferation of the magnetite on the inside of the ferrihydrite deposits in the last mineralized teeth of stage 2. The other point is that the continuing accretion of magnetite in the tooth caps in stages 3 and 4 is always preceded by the development of ferrihydrite. This not only reinforces the previously offered interpretation of a ferrihydrite precursor for the magnetite (6) but extends it to all stages of the magnetite development. Without the ferrihydrite veneer at stages 3 and 4 this magnetite would appear to be a direct precipitate.

The transformation of ferrihydrite ($5 \text{ Fe}_2\text{O}_3 \cdot 9 \text{ H}_2\text{O}$) to magnetite ($\text{FeO} \cdot \text{Fe}_2\text{O}_3$) involves (a) reduction of $1/3$ of the ferric iron to the ferrous state, (b) removal of oxygen, (c) dehydration, and (d) a change from hematite-like hexagonal close packing to a cubic inverse-spinel structure (6,9). This conversion takes place while the superior epithelial cells of the radular sac are still tightly adhering to the tooth caps; hence it is controlled solely by the biochemistry of the organisms. Although the precise mode of the transformation process has not been determined, it is probably mediated by one or more enzymes.

Concerning the later added minerals, francolite in C. tuberculatus and the amorphous, hydrous ferric phosphate in C. stelleri seem to be directly precipitated in this form. Lepidocrocite in C. tuberculatus teeth, however, may have a ferrihydrite precursor like the magnetite. This ferric oxide phase has been synthesized in the laboratory as the end product of the following precipitation sequence: Ferrihydrite → Green Rust I → Green Rust II → Lepidocrocite. This involves only topotactic transformation but no major crystallochemical changes (12, 13, 14).

In cold and temperate water species the mature teeth consist of about 65 percent magnetite and 35 percent amorphous hydrous ferric phosphate. Magnetite in the warm water species forms only one third of the mineralization products and the balance consists of lepidocrocite and francolite (1, 7, 27). It thus appears that at higher oceanic temperatures the colloidal ferric phosphate formed at lower temperatures is replaced by 2 crystalline materials, a ferric oxide and a phosphate mineral (27).

3. TOOTH CAP CONSTRUCTION

Gross morphology. Chiton teeth are either one to three pronged in form or blade shaped (Fig. 2). Each species has only one of these cap morphologies and hence they are shown to be genetically fixed. In an individual, the cap shape is established in the first, newly formed unmineralized teeth and remains unchanged in the subsequent mineralization process. In the following, consideration is extended only to aspects concerning the magnetite of the tooth caps.

Ultrastructure. Scanning electron micrographs reveal several features which are common to all species examined: 1. The thickness of the magnetite layer rarely exceeds 10 μ m. (Fig. 3 a,b). 2. The magnetite bearing surfaces of mature teeth are shown in low resolution SEM micrographs to be subdivided into grossly hexagonal polygons of about 5 to 7 μ m in diameter (Fig. 3c, d). The polygons are bounded by a wall of organic matrix material, <0.05 μ m in diameter, which is thickest and hence most conspicuous in areas where the ferrihydrite has not yet been transformed into magnetite (Fig. 2c). Cross-sections of the tooth caps show that the organic network bordering the polygons projects as a sheet vertically through the magnetite layer, even at the ferrihydrite stage (Fig. 3b). 3. As seen in high resolution micrographs the polygons are filled with a thin-walled organic framework or honeycomb which completely envelops initially the ferrihydrite and later the magnetite grains. Towe and Lowenstam (6) have shown using transmission electron microscope replica that these walls are further composed of fibrous material. The individual magnetite grains are nearly equant in dimensions (6) and have not been observed to penetrate the organic matrix walls. Data obtained by X-ray diffraction, electron microscopy and magnetic property determinations are consistent with the interpretation that the individual magnetite grains are single crystals.

The size and shape of the magnetite grains largely determine their magnetic properties, which are considered next.

4. MAGNETIC PROPERTIES

Grain-size distribution. The importance of magnetite as a carrier of stable fossil magnetism (paleomagnetism) in rocks has led to a great deal of experimental and theoretical work on its magnetic properties [15-20]. Chief among the physical parameters which control the properties of monocrystalline magnetite are the size and elongation of individual grains [16]. Our electron micrographs discussed earlier can therefore be used to predict the behavior of magnetite derived from various chiton species. We measured individual grain lengths and widths from local areas on the surface of the teeth after a brief cleaning with Clorox. Figure 4 shows the resulting scatter diagram of grain size vs. the axial ratio (width/length) from mature teeth of three chiton species (C. stelleri, C. tuberculatus, and Lepidopleurus sp.). Because the grains are generally equant, the scatter of axial ratios measured on the cleaned surface should reflect the average 3-dimensional range. In each case the grain size distribution is remarkably narrow and centered in the vicinity of about 0.1 μm , sharply contrasting with the high-variance, generally log-normal size distributions generated by sediment transport and crystal growth processes [21,22]. Although the distributions partially overlap, species with larger teeth (C. stelleri) have on the average a grain size greater than those of smaller individuals (Lepidopleurus sp.). The axial ratio (width/length of the grains) is more or less uniformly distributed between 0.4 and 1.0, indicating the forms are not highly elongate.

Magnetic stability. Superimposed upon the scatter diagram of Fig. 4 are magnetite's theoretically-derived boundaries for single-domain (SD), two-domain, and superparamagnetic (SPM) behavior, assuming room temperature and parallelepiped shapes [16]. Single-domain grains are those in which a uniform, parallel magnetic spin structure exists across the entire volume of the particle; magnetic directions in these grains are immortal, remaining

unchanged through long periods of geologic time [23]. For this reason, single domains are extremely important as carriers of natural remanent magnetism in both igneous and sedimentary rocks. Above the upper boundary shown on Fig. 4 this single domain configuration becomes unstable, the atomic moments no longer align themselves uniformly through the particle, and two or more domain states are produced which sometimes mimic aspects of single domain behavior (pseudo-single domain behavior [15, 16]). Below the bottom two curves on Fig. 4, thermal activation destroys the immortality of the magnetic remanence and the moments from each domain will quickly randomize themselves or preferentially align with local magnetic fields, yielding superparamagnetic behavior [23].

Using the scatter diagram and stability fields shown on Fig. 4, we find that a large fraction of chiton-derived magnetite plots within the theoretical single domain area with some species-dependent variation. C. stelleri is spread between the SD and PSD fields, C. tuberculatus is primarily SD, and Lepidopleurus sp. falls in both SD and SPM areas. Care should be taken, however, because boundaries between these stability fields were calculated for isolated, rectangular magnetite parallelepipeds [16]. Chitons differ from this in two respects: (a) the magnetite crystals are somewhat irregular in shape, not rectangular parallelepipeds, and perhaps most importantly (b) the grains in chiton teeth are closely packed against one another, separated only by a film of organic material. Effects of this close packing in naturally-occurring rocks are generally minor [22],

but because local fields at this distance may be on the order of several hundred oersteds [24], their behavior may differ greatly from that predicted for isolated grains on Fig. 4. In particular, Morish and Watt [25] conclude that interactions may increase the SD/MD transition size, implying that most C. stelleri crystals may actually behave as stable single domains.

SPM and MD tests. The domain state can partially be determined by examining a number of magnetic properties of the teeth. Superparamagnetic grains, if present, are sometimes distinguished on Curie temperature curves because their magnetization will decay slightly faster with temperature than ferromagnetism, yielding somewhat flattened or concave upwards paths. These curves (Fig. 5) suggest that C. stelleri has few superparamagnetic grains, but C. tuberculatus may have small amounts as predicted by Fig. 4. Curie temperatures for both species are slightly above the normal 580°C value typical for pure magnetite and may reflect the presence of minute amounts of Al and other trace elements [1]. An additional test for superparamagnetic grains is to monitor the remanent magnetism as the sample warms from liquid nitrogen temperature (-196°C) after exposure to a strong, saturating magnetic field (~300 mT or 3000 oe.). Néel theory predicts that at -196°C magnetite crystals only 200Å in diameter should be able to hold stable remanence; as these grains individually warm through their blocking temperature they become superparamagnetic and cannot hold permanent magnetism. Results of these experiments shown in Fig. 6 indicate the Lepidopleurus has a much larger fraction of SPM grains (200 - 300Å) than C. stelleri. On the subsequent cooling and warming cycles shown, the teeth have at most a minor drop in remanence as they warm through the isotropic point of magnetite (~143°C), indicating that multi-domain grains contribute little to the remanence [15], in agreement with the predictions of Fig. 4.

Alternating-field stability. Isolated magnetite grains comparable in size and shape to those from C. stelleri (Fig. 4) have been found previously to be fairly resistant to alternating-field demagnetization; rocks with remanence carried by such grains generally lose half of their magnetization after treatment in alternating fields above 40 mT (400 oe.) [15, 22]. We checked this prediction by progressively demagnetizing the natural remanent magnetism (NRM) of 5 mature C. stelleri teeth (Fig. 7). Surprisingly, in each case we found median destructive fields (m.d.f.) near 12 mT (120 oe.), values more typical of larger, multi-domain grains [17]. This discrepancy is probably due to close interactions between neighboring domains which are separated by only 200 Å of organic matrix [6]. Dunlop and West [22] discuss the grain-grain interaction problem, and conclude that the net result is to reduce the stability of a sample to AF demagnetization. This anomalously low AF stability exhibited by chiton teeth should characterize their biogenic magnetite even after it is worn down and shed into the marine environment.

Care is therefore needed when one attempts to use AF demagnetization as an indication of domain configuration in marine sedimentary rocks; procedures such as the Lowrie-Fuller test [17] might not distinguish between multi-domain configurations and closely interacting single domains.

Natural Remanent Magnetism in Chitons. During the rapid conversion of ferrihydrite to magnetite, each tooth acquires a natural remanent magnetization in the Earth's magnetic field. Although each crystal essentially behaves as a single domain and is magnetized fully to saturation, the drive toward minimum magnetostatic energy dictates that neighboring grains will pair their moments in order to reduce the net external field. Any final remanence produced by a slight statistical bias from the local magnetic field will be much less than the maximum possible value.

We must estimate the size of this natural remanence because it ultimately contributes to the magnetization of sediments. Fig. 8 shows the direction and intensity of the natural remanent magnetization of individual teeth along one half of a C. stelleri radula. Each tooth from this individual was removed with non-magnetic dissecting tools and orientated on the sticky surface of a 25 mm square glass slide. These samples were measured using a SQUID magnetometer [26] and the results compared with the shape and orientation of the tooth. The large central prong of the C. stelleri tooth (Fig. 2b) generates enough shape anisotropy to constrain the remanence along its axis, thereby deflecting it from following the direction of the Earth's magnetic field. Old teeth near the anterior end of the radula generally have slightly higher remanence ($\sim 5 \times 10^{-6}$ emu or Gauss $\cdot\text{cm}^3$) than younger ones, reflecting the continued conversion of ferrihydrite to magnetite as they mature. The youngest teeth shown on Fig. 8 which were formed during the animal's 2-week life in our laboratory are anomalously intense ($\sim 5 \times 10^{-4}$ Gauss $\cdot\text{cm}^3$); they were mineralized in stronger, local magnetic fields and hence do not represent natural conditions. Mature C. stelleri teeth on the average contain 4.7×10^{-5} gram of magnetite, and thus have a natural level of magnetization near $0.1 \text{ Am}^2/\text{kg}$, far below the saturation value of $\sim 93 \text{ Am}^2/\text{kg}$. Studies on other species yield comparable results, so it is likely that most chiton magnetite will have similar levels of magnetization when shed into the environment.

5. CONTRIBUTION OF CHITON MAGNETITE TO THE MAGNETIZATION OF SEDIMENTS

Based on observed population densities and rates of tooth formation, Lowenstam [27] estimated that chitons annually shed 3.9×10^9 g of iron to oceanic sediments, corresponding to 5.4×10^9 g of magnetite. Although the bulk of this material is generated by dense chiton populations in the intertidal and shallow subtidal zones of all oceans, small amounts are produced by species which live at depths down to almost 7000 meters. Teeth which have been crushed in the laboratory generally tend to break along the hexagonal walls of organic matrix (Figs. 3c & d), and we therefore predict that the similar processes of tooth wear will produce fragments $\sim 5 \mu\text{m}$ and smaller which would be easily dispersed in the marine environment. If we assume that this material is distributed evenly along the $43.7 \times 10^6 \text{ km}^2$ of continental margins and slopes above a depth of 1 km [28], the annual contribution to the sediments of magnetite is about $1.3 \times 10^{-6} \text{ gram cm}^{-2}\text{yr}^{-1}$. Given the natural level of magnetization for chiton particles of $0.1 \text{ Am}^2/\text{kg}$ noted above, we estimate an average annual magnetic contribution to the sediments on the order of $10^{-7} \text{ Gauss}\cdot\text{cm}/\text{yr}^{-1}$. A sedimentation rate of $10^{-3} \text{ cm}/\text{yr}$ and a 1% alignment efficiency would then yield a DRM intensity near 10^{-6} Gauss . Even after dilution by other highly variable sources of sedimentary material, it seems possible that chiton magnetite contributes a significant fraction to the magnetization of sediments.

6. OTHER BIOLOGIC SOURCES OF MAGNETITE

Arthropods. Gould, Kirschvink and Deffeyes [4] discovered that under certain conditions honey bees develop a weak, stable magnetic remanence. Curie temperatures, saturation magnetization, and low-temperature cycling implied the presence of about 10^{-8} gram of fine-grained magnetite per individual, including a considerable amount of superparamagnetic material. Behavioral experiments have shown that honey bees are sensitive to the direction and intensity of local magnetic fields, and it seems probable that the magnetite is part of the detection organ. A preliminary survey of 18 other invertebrate species revealed 5 with comparable magnetic remanence. At this stage we may speculate that as a whole the Arthropods could contribute magnetite to marine, fresh water and terrestrial sediments, but their generally low population density suggests the total amounts are minor.

Vertebrates. Walcott, Gould and Kirschvink [5] extended the above study to the homing pigeon which also navigates using the magnetic field. In each bird examined, a small magnetic region was discovered along the inside surface of the skull. The remanence was associated with a small amount ($\sim 10^{-7}$ gram) of 0.08-0.15 μ m diameter, iron-rich black material. Curie temperatures and low-temperature cycling revealed this material to be single domain magnetite, again probably part of a magnetic field detector. Additional work on other vertebrates is in progress, but it seems unlikely that enough magnetite is bioprecipitated by this group to be of significance to the magnetization of sediments.

Mud Bacteria. Blakemore [2] reported a new type of flagellated mud bacteria that is strongly influenced by the direction of local magnetic fields. His transmission electron microscopy revealed that each bacterium contained two linear chains of electron-opaque tabular particles, each chain

containing between 5 and 10 grains. To date, these anaerobic or micro aerophilic bacteria have been found in salt and fresh water peat bogs, marshes, and in the surface layers of shallow sedimentary cores. Using Mössbauer absorption, Frankel, Blakemore, and Wolfe [3] have recently identified the opaque material as magnetite.

On Fig. 4 we have plotted the size and shape range of the mature bacterial grains as measured from Blakemore's [2] electron micrographs. Although they were reported as tabular in shape, an estimate of the grain thickness could not be made from their photographs. The axial ratio as plotted on Fig. 4 could conceivably vary within the horizontal boundaries of the dashed, rectangular box shown. Despite this uncertainty, the bacterial magnetite crystals fall entirely within the single domain stability field and should be capable of carrying immortal magnetic remanence.

Alternating-field demagnetization studies have not yet been reported on bacterial magnetites, but the blocking and unblocking field strengths were directly measured in a unique way. Noting that living magnetotactic bacteria will align themselves and swim parallel to local magnetic fields, Kalmijn and Blakemore [29] applied short, one-shot magnetic pulses of varying strength to entire free-swimming populations. If the short pulse exceeded the blocking or unblocking field of the magnetite domains within a bacterium, their polarity would switch and it would suddenly swim in the opposite direction. Field strengths of 37.5 to 40 mT were necessary to flip the polarity of their freshwater specimens, while 52.5 to 55 mT pulses were effective on the marine species. In contrast to chiton magnetites, grain-grain interaction fields do not seem to seriously affect bacterial domains. The cause of the stability difference between marine and freshwater species was not discussed by Kalmijn or Blakemore, but we speculate that it could be

due to small species-dependent differences in the domain shape anisotropy which contribute to the microscopic coercive force. If the absolute size and shape of these tabular bacterial magnetite grains is uniform within a given strain, it might be possible to isolate species with distinctly different tabular morphologies. Magnetite powders derived from these cultures should plot in discrete regions in Fig. 4, and perhaps be of use for testing the theoretical boundaries calculated by Butler and Banerjee [16].

Blakemore [27] made estimates of bacterial population densities which can be used to roughly place a minimum estimate on the paleomagnetic significance of these organisms. Each domain within the bacterial size range shown on Fig. 4 would contain between 2 and 6×10^{-15} gram of magnetite, depending upon the thickness. Every bacterium had between 10 and 20 particles, so there should be between 2 and 12×10^{-14} gram per cell. Natural population densities range from 200 to 1000 per ml, but after an ecological succession these numbers can reach several hundreds of thousands. Using $10^5/\text{ml}$ as a conservative estimate of the cumulative population, we therefore expect anywhere from 2 to 12×10^{-9} gram of single domain bacterial magnetite per ml of uncompressed sediment, corresponding roughly to a saturation magnetization near 2 to 12×10^{-7} Gauss. Using a conservative sediment compaction ratio of 50% along with a 1% efficiency of alignment, the DRM intensities would be from 4 to 24×10^{-9} Gauss. A 10cc paleomagnetic sample then has a moment of $4 - 24 \times 10^{-8}$ Gauss $\cdot\text{cm}^3$, just above the 10^{-8} Gauss $\cdot\text{cm}^3$ sensitivity of SQUID magnetometers [26].

Although numerous organic sediments including coal, peat, and biogenic ooze have been reported to contain stable remanence which has sometimes been related to fine-grained magnetite or titanomagnetite, bacteria have not been previously considered as a possible source for the remanence [30-34]. Very little has been reported about the biology or geographic distribution of

magnetotactic bacteria, but one may guess that their swimming response is useless in nature without the geomagnetic field. Since bacteria and the geomagnetic field both seem to have evolved very early in Earth history, magnetotactic organisms may have been supplying single domain magnetite during Precambrian as well as Phanerozoic time. Conversely, the existence of bacterial magnetite flakes in early Precambrian sediments such as black cherts would paleontologically imply that the Earth's magnetic field, and presumably the core, had formed.

7. CONCLUSIONS

1. Magnetite precipitation in chitons is a 4 stage continuous process. After formation, the initial sponge-like organic matrix is infilled with the mineral ferrihydrite probably derived from the iron-storage protein ferritin. The bulk of the iron is rapidly converted to magnetite at the beginning of the third stage of development, followed thereafter by minor amounts of ferrihydrite deposition and subsequent reduction to magnetite. Because the ferrihydrite to magnetite reaction is not topotaxial, it must be controlled by as yet unrevealed biochemical pathways.

2. Although the external morphology of chiton teeth varies with species, they all have irregular hexagonal subunits roughly 5 μm across and individual magnetite grains near 0.1 μm in diameter. Grain-size distributions generally have little variance, contrasting sharply with other natural magnetite forming processes. Individual grains generally have width/length ratios greater than 0.4.

3. The bulk of chiton magnetite should possess single domain or pseudo-single domain magnetic behavior, allowing it to carry immortal remanence. Grain-to-grain interactions drastically reduce the stability of chiton teeth towards alternating-field demagnetization, yielding natural magnetization values near $0.1 \text{ Am}^2/\text{kg}$. This anomalous AF stability could be mistaken for multidomain behavior in sedimentary rocks.

4. Biogenic magnetites are a potential source of stable remanent magnetism in sediments and sedimentary rocks, but have not yet been conclusively identified in Nature. We expect the fragments of less than 5 μm diameter to associate with similarly fine-grained sediment.

ACKNOWLEDGEMENTS

This work was supported in part by NSF grant EAR78-03204 to JLK and EAR - to HAL. Some of the magnetic experiments were done at the U. S. Geological Survey in Flagstaff, Arizona and at the Australian National University in Canberra, Australia. Helpful advice through the course of this work was given by M. W. McElhinny, R. B. Hargraves, R. T. Merrill, and D. Champion. R. F. Butler and K. M. Towe reviewed the manuscript.

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Fig. 1A. Location of a Chiton's radula.

Fig. 1B. Mineralization pattern of chiton teeth. Chiton tuberculatus is a typical warm water species from Barbados, and Cryptochiton stelleri is a large cold water species from California. The radula is positioned as shown in Fig. 1A and the sequence of mineralization is discussed further in the text.

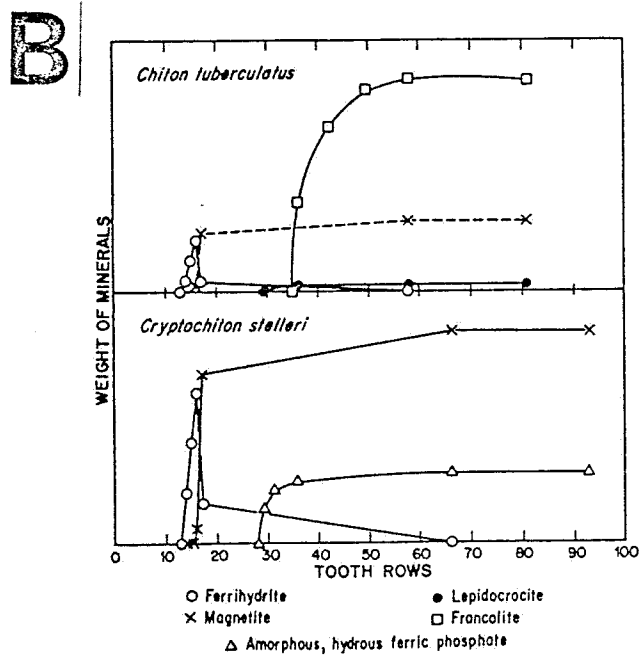
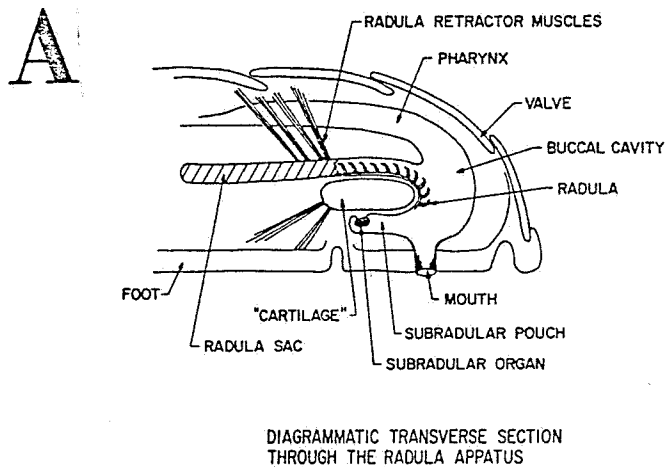


Fig. 2. Scanning electron micrographs of typical chiton teeth.

(a) Chiton tuberculatus (from Barbados), (b) Cryptochiton stelleri (California), (c) Henleya henleyi. The surface layer of ferrihydrite which continually converts to magnetite is clearly seen on the lower right portion of 2(c).

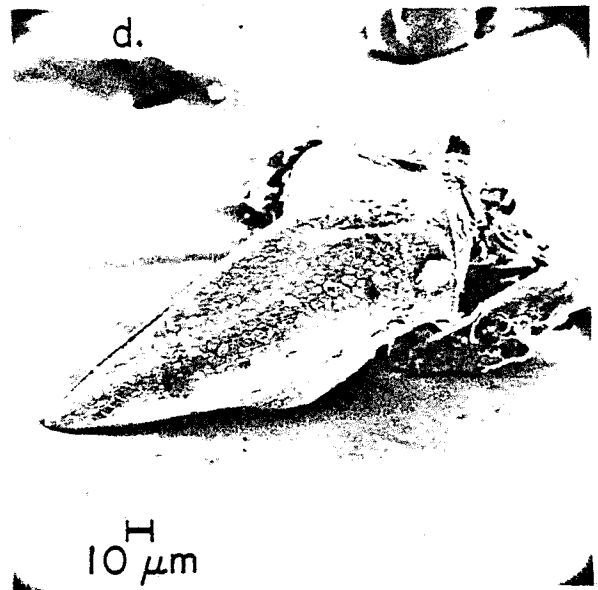
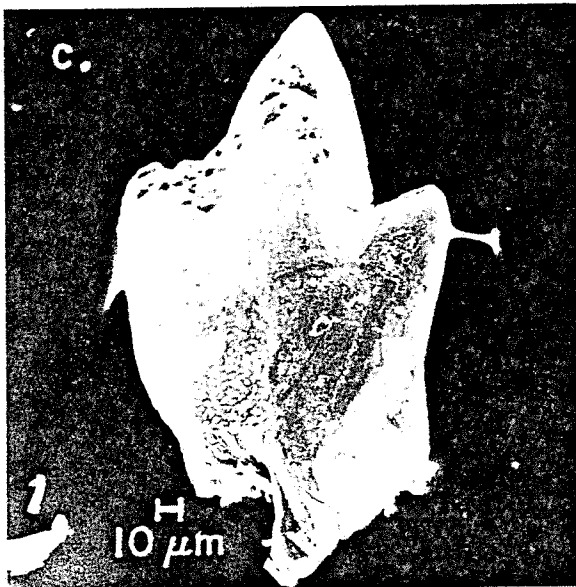
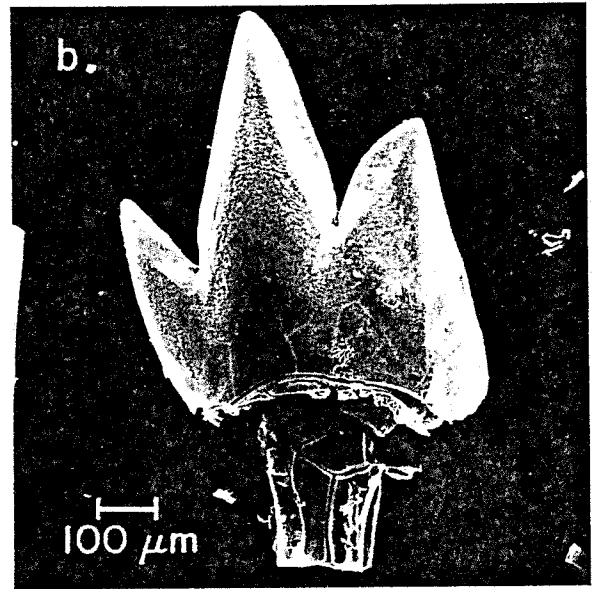
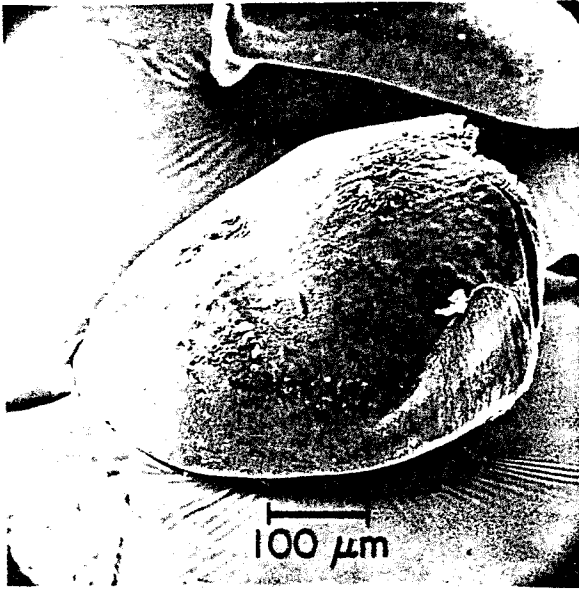


Fig. 3 (a & b) Fractured surfaces of H. henleyi tooth. The outer, fairly resistant layer is of magnetite while the central core is the amorphous, hydrous ferric phosphate. Fractures seem to propagate along walls of the organic matrix. (c) Hexagonal subunits and newly-formed organic matrix network of Henleya henleyi. Small amounts of ferrihydrite are continually added and converted to magnetite in these local patches during maturation. (d) Fully mineralized surface of a Chiton tuberculatus tooth, showing the ~5 μm hexagonal subunits and the ~0.1 μm magnetite crystals within the organic matrix. All teeth were etched slightly with Clorox, washed and thoroughly dried before coating with gold-palladium.

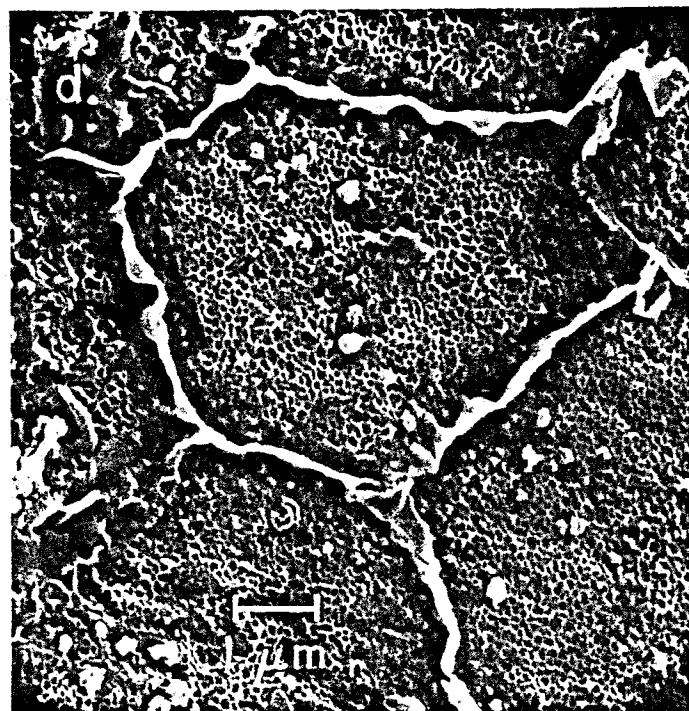
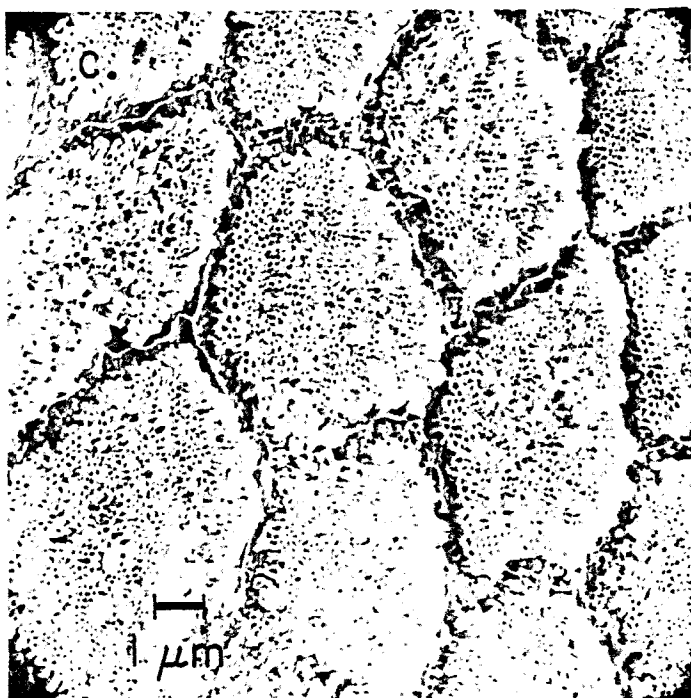
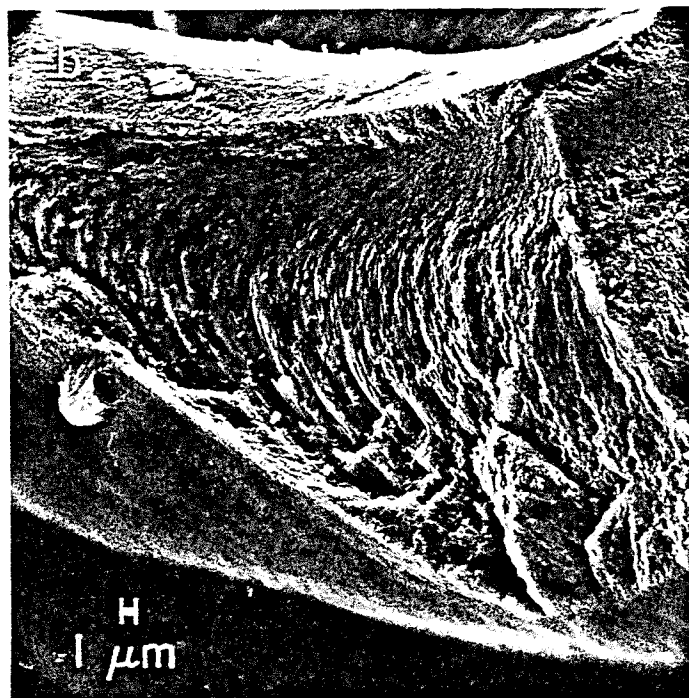
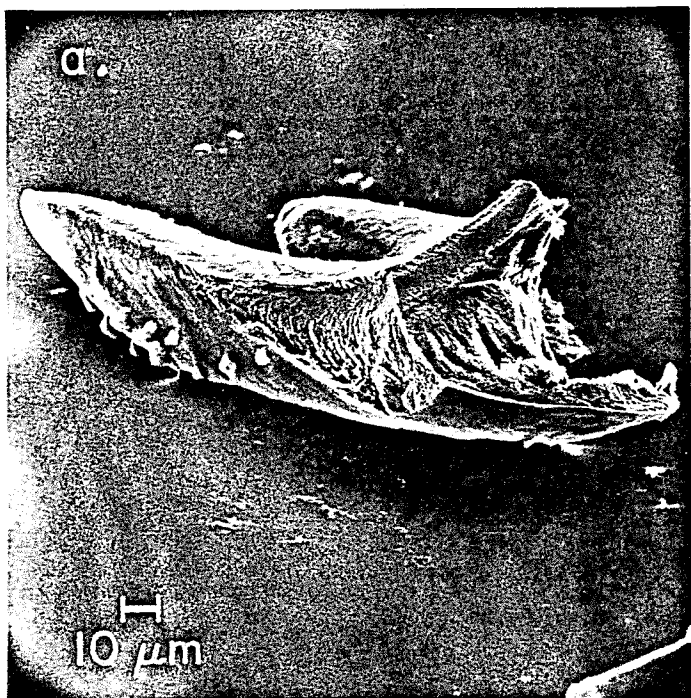


Fig. 4. Grain-size distribution and predicted domain and magnetic stability configurations. The lengths and widths of all adjacent magnetite grains from local areas on 3 mature chiton teeth were measured from electron micrographs and plotted as shown. Boundaries between the two-domain, single domain, and superparamagnetic stability fields for isolated rectangular parallelepipeds of magnetite were drawn according to the calculations of Butler and Banerjee [16]. The dashed rectangular box drawn within the single domain field plots the size and axial ratio of bacterial magnetite flakes measured from Blakemore's [2] electron micrographs.

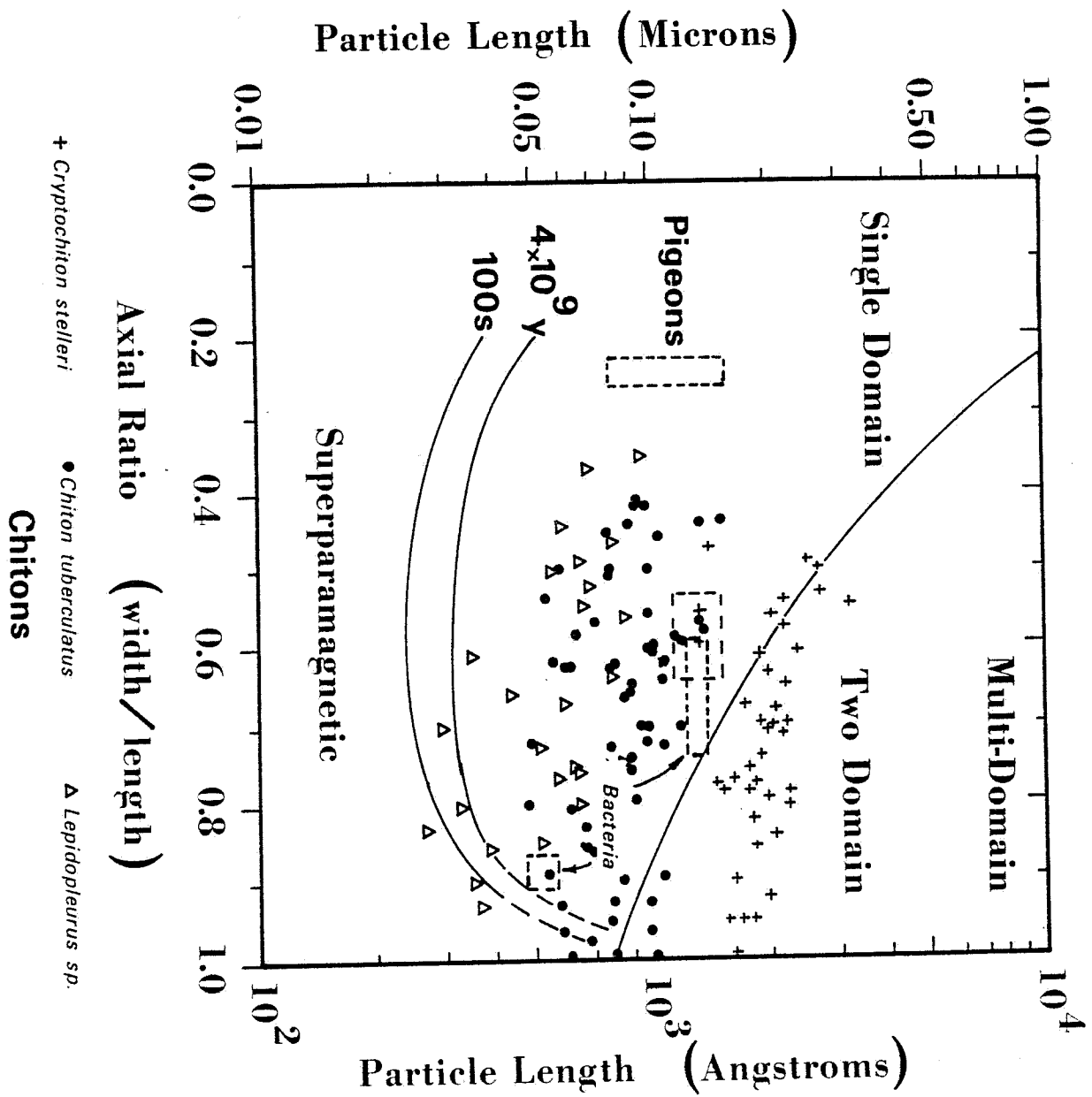


Fig. 5. Curie temperature curves for C. tuberculatus and C. stelleri.

Measurements were made under vacuum in magnetic fields of 800 mT (8koe.).

Black circles indicate relative magnetization values during the warming phase, and squares indicate the return cooling path. The somewhat linear and concave-upwards portion of the C. tuberculatus path between 100 and 400°C suggests the presence of some superparamagnetic material not present in C. stelleri.

Both species have Curie temperatures near 590°C, suggesting the presence of small amounts of impurities [1]. Magnetization values increased slightly during the heating experiment, reflecting the high-temperature reduction of adjacent iron rich supporting minerals (Fig.1) to magnetite.

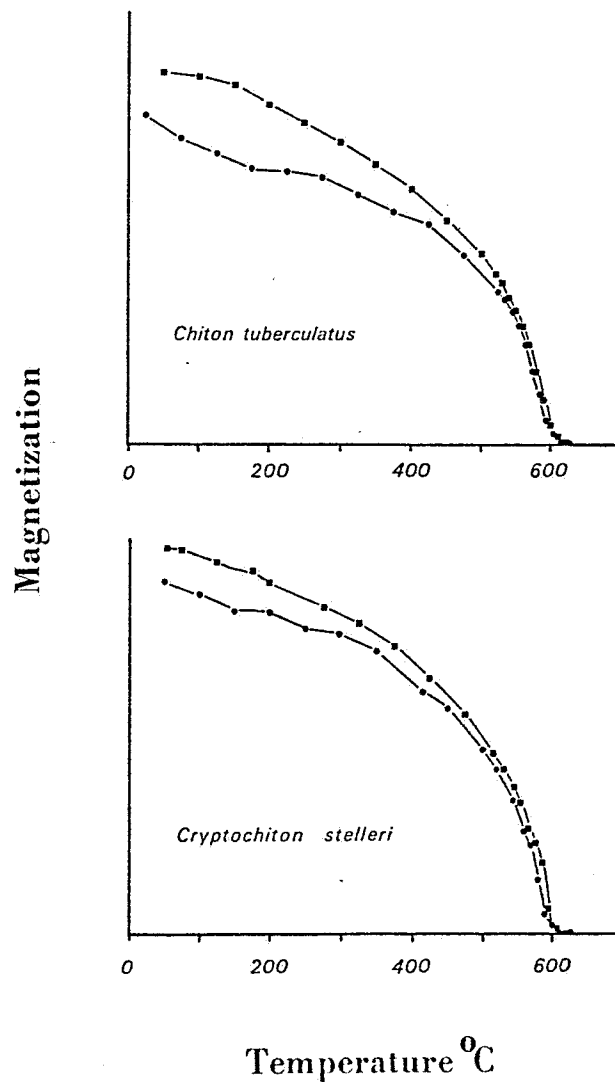


Fig. 6. A test for superparamagnetism. Teeth from Lepidopleurus sp. and C. stelleri were placed in a 300 mT (3 Koe) magnetic field and cooled to -196°C in liquid nitrogen, and subsequently were allowed to warm inside a SQUID magnetometer. At this temperature, magnetite crystals 200 to 400 Å in diameter should behave as single domains and carry stable remanent magnetism; at room temperature they are normally superparamagnetic. Upon warming, the remanence will decrease as small crystals warm through their blocking temperatures and as the saturation magnetism decreases slightly. Lepidopleurus sp. loses about half its remanence during this first warming, reflecting the difference in grain size between it and C. stelleri plotted on Fig. 4. Additional, gradual remanence decay which was noted in both species during subsequent warming cycles probably results from a small fraction of grains which are slightly viscous at room temperature.

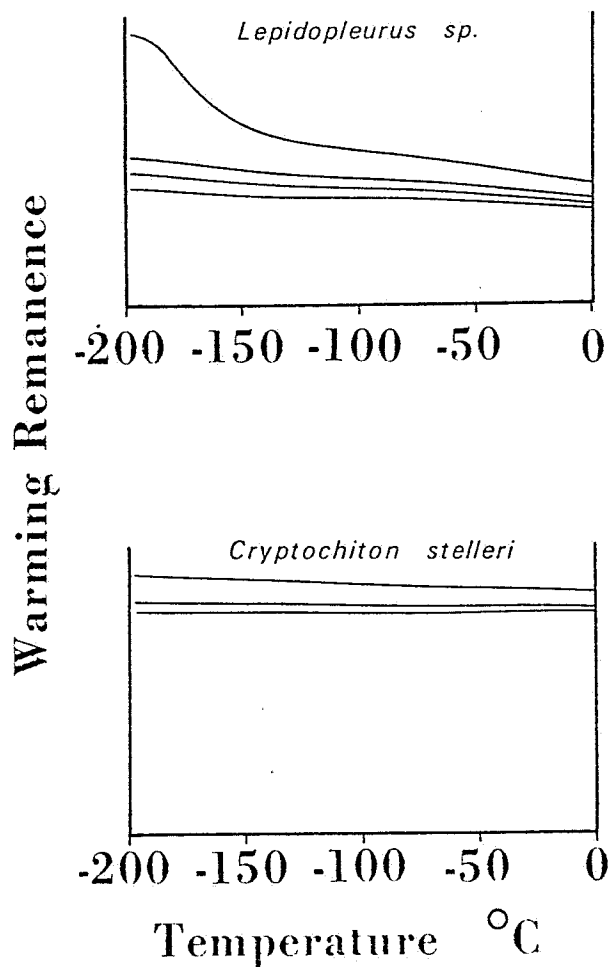


Fig. 7. Alternating - Field demagnetization of the NRM of five mature Cryptochiton stelleri teeth. Average medium destructive fields are anomalously low for single domains at only 12 mT (120 oe.).

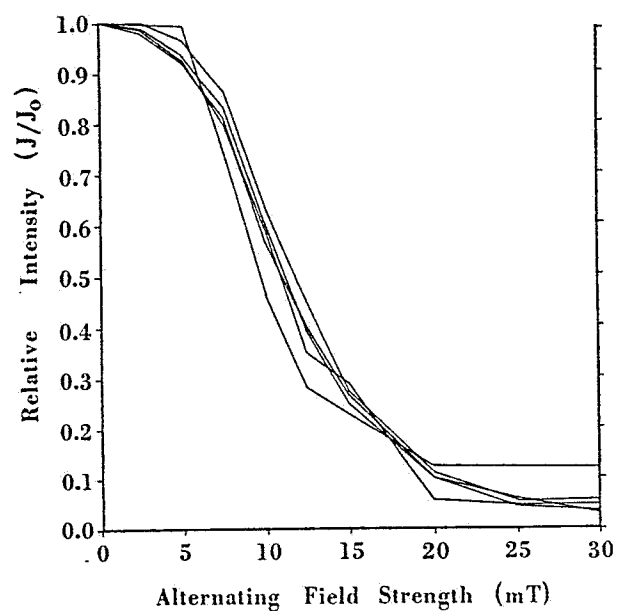
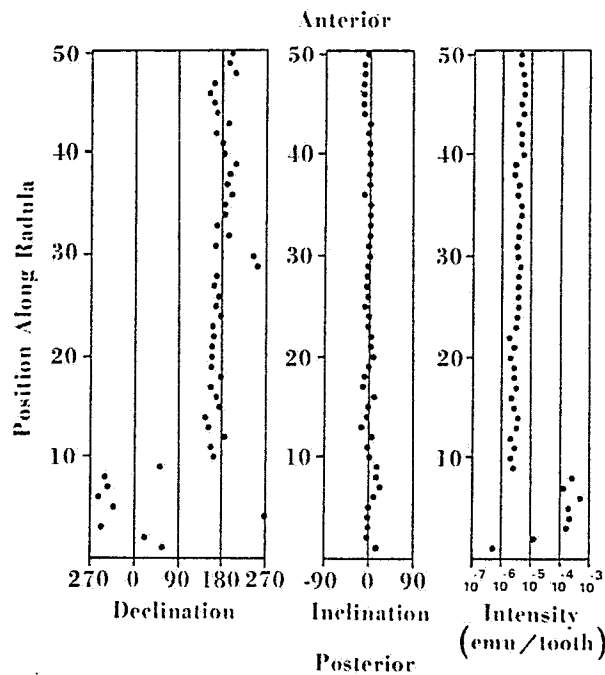


Fig. 8. Magnetic directions and intensity of sequential teeth along the radula of a young Cryptochiton stelleri. Declination values were measured clockwise from the central prong shown in Fig. 2(b), and positive inclinations were measured downward from the plane of the photograph. Teeth beyond row 8 were mineralized and magnetized before the animal was captured, whereas the first 8 rows formed during 2 weeks in our laboratory under artificially high fields. In most teeth, the natural remanence is antiparallel to the central prong and lies within the plane of the tooth. This suggests that the magnetic direction is influenced more by the shape anisotropy of the tooth than by the local magnetic field direction. (note: $1 \text{ emu/g} = 1 \text{ Am}^2/\text{kg}$).



Organic Magnetite: A ferrimagnetic basis for magnetic field detection
in animals

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Abstract

Biologically precipitated magnetite (Fe_3O_4) has been found recently in a diverse variety of organisms including bacteria, insects, and vertebrates. Its mineralization in localized areas seems to be associated with the ability of these animals to detect the direction and intensity of the earth's magnetic field. The presence of both superparamagnetic and single domain magnetite crystals in large numbers ($\sim 10^8$) implies that they may have at least two basic types of magnetic field detection organs, one of which is permanently magnetized (single-domain) and one which is not (superparamagnetic). Theoretical calculations show that such ferrimagnetic organs or organelles when connected in large numbers to the nervous system are capable of accounting for most of the magnetic field sensitivity observed in animals. Several models for the arrangement of magnetite grains within these organelles are considered and, where possible, compared to the behavioral data.

INTRODUCTION

The behavior and, in particular, the orientation of a variety of aquatic and terrestrial animals is said to be affected by the direction and/or intensity of the earth's magnetic field. This menagerie includes, for instance salamanders (Phillips, 1977), robins (Wiltscho and Wiltscho, 1972), planarians and snails (Barnwell and Brown, 1964), newts (Adler, pers. comm.), bacteria (Blackmore, 1975), termites (Becker, 1976), roaches (Becker, 1971), flies (Wehner and Labhart, 1970), skates (Brown, et al, 1974), sharks (Kalmijn, 1978), gulls (Southern, 1975), gerbils (Shotz, 1971), and humans (Rocard, 1964). The behavioral phenomena associated with magnetic field sensitivity are particularly dramatic and accessible in honey bees, bacteria, and homing pigeons.

Honey Bees

There are four magnetic field effects reported in the honey bee literature. The first is that the characteristic residual direction error in the honey bee dance depends on the earth's field. The misdirection is always zero for dances along the earth's field lines and in an approximate null field (Lindauer and Martin, 1968), but otherwise depends very clearly on the orientation of the dance with respect to the earth's field and, from empirical curve fitting, on the rate of change of the earth's field strength (Lindauer and Martin, 1972; Martin and Lindauer 1977). This dynamic field effect is curious since it ought not to be affected by static field strength, and yet it disappears when the static field component is decreased to less than 4% or increased to more than ten times normal, and is exaggerated in static fields of three to eight times normal.

Then, too, to make the prediction fit the data more closely, additional terms with ambiguous signs must be introduced to take account of an apparent saturation of the dynamic system for field changes greater than approximately

2×10^{-5} to 2×10^{-6} earth's field per minute (Martin and Lindauer, 1977).

(The exact rate depends on the rate of the sun's azimuth movement.) The same phenomenon of orientation lagging behind a too-rapid change in field strength is seen when the static field is cancelled, yet the misdirection disappears only gradually, over the course of 40-45 minutes (Lindauer and Martin, 1972). The product of these adumbrations and the judicious addition (or subtraction) of the secondary terms is an often rough but nevertheless striking fit of the behavioral data. The selective advantage of this magnetic misdirection of the dance is obscure.

The second evidence of magnetic orientation in honey bees emerges when foragers are forced to dance on horizontal comb. When the bees are deprived of their normal gravity reference and all visual cues, dances are rare and randomly oriented. After about two weeks, however, a high proportion of those bees that will dance under these conditions are oriented to the eight cardinal points of the magnetic compass. Cancelling the static field causes the dances to become disoriented, while increasing the field strengthens the magnetic orientation, particularly to magnetic North, South, East, and West. As with misdirection, fields stronger than ten times normal abolish orientation (Lindauer and Martin, 1972; Martin and Lindauer, 1977). Since the dance orientation in the hive is unrelated to the location of food, the utility of this behavior is unknown. It looks very much like the spontaneous but senseless quadramodal or octomodal orientation of invertebrates to detectable but context-irrelevant stimuli such as polarized light.

A third reported effect is that in the absence of other cues, bees building comb in an otherwise featureless hive will align the sheets in the same magnetic direction as the comb in the parent hive. Strong magnetic fields are said to disrupt comb orientation (Lindauer and Martin, 1972; Martin and Lindauer 1973). Although there would be a selective advantage if the thousands of comb-builders were able to "decide" on a consistent

comb orientation, repetitions of this experiment in this country have failed.

The final effect discovered to date of magnetic fields on bees is the reported ability of the weak but roughly regular daily variations in field strength generated by ion flow in the upper atmosphere to set the circadian rhythms of foragers in the absence of other cues (Lindauer, 1976). The evidence for this is somewhat indirect. In a normal earth's field, bees in a constant-condition flight room will forage with a 24-hour periodicity, displaying little sign of the drift which characterizes a free-running period. In a ten times normal earth's field, however, the bees do not return to the food source on schedule; and on certain days of abnormally high magnetic activity (resulting from major changes in ion production by the sun), the time sense of trained foragers seems correspondingly impaired. Then, too, translocations of a trained hive to similar flight rooms in regions with relatively different patterns of daily variation had a larger effect on the time sense of trained foragers than translocations to areas with roughly similar daily patterns. An adaptive significance for such a system can be imagined for highly social animals which live in cavities out of sight of the sun, but reconciling this data with other work on honey bee circadian rhythms (e.g. Renner, 1957, 1959; Bennett and Renner, 1963) presents difficulties.

Homing pigeons

Homing pigeons show less reliable but more obviously adaptive responses to the earth's field than do honey bees. In getting back to the loft from an unfamiliar release site, pigeons behave as if they know where they are and which direction is which--that is, as if they have both a map sense and a compass. The sun is their primary compass, and clock-shifted pigeons are

able to choose an appropriate (though less accurate) bearing under overcast (Keeton, 1969). This backup compass is sensitive to magnetic fields. The static field of a bar magnet (Keeton, 1971) or Helmholtz coil (Walcott and Green, 1974) attached to the head disrupts orientation dramatically, but only on cloudy days. Pigeons seem to judge "north" by the maximum dip angle rather than the polarity of the field (Walcott, 1974). Robins, too, seem unable to distinguish polarity (Wiltscho and Wiltscho, 1972), and there is no evidence that bees can either.

Like honey bees, pigeons are also affected by small, dynamic changes in field strength. Even on sunny days, magnetic storms produce small, irregular but roughly graded deflections of departure bearings (Keeton, et al, 1974), while releases at magnetic anomalies increase the scatter of departure bearings in proportion to the magnetic "bumpiness" in the homeward direction (Walcott, 1978). These dynamic effects can be interpreted either as a sunny-day interaction between the solar and magnetic compasses, or, since some anomalies can completely disorient birds on sunny days while far stronger coils and magnets have no effect when the suncompass is available, as a component of the mysterious map sense.

DETECTOR STRATEGIES

Although some animals are certainly sensitive to the earth's magnetic field, little is known about how the underlying sensory mechanism(s) might work. There are, however, only three general strategies with the potential of providing magnetic field information to the nervous system: induction, permanent magnetism, and paramagnetism (Gould, et al, 1978).

Induction

The first mechanism is based on Faraday's law; a conductor moving

through a magnetic field will produce an electric potential. Depending on the geometry and physical setting of the conductor, this potential may result in either a flow of current or the maintenance of an electrostatic field. This method seems to be the system employed by saltwater elasmobranch fish (Kalmijn, 1978) and stationary seawater acting as a volume conductor completes the external circuit. Current flow is detected by the ampullae of Lorenzini, and provides sufficient sensitivity to detect the earth's field at speeds of as little as 1cm/sec (Kalmijn, 1978). The same system in freshwater fish is 10^2 less sensitive and, since air would have to act as the return path, is unworkable in this form in terrestrial animals. (The magnetic sensitivity of the elasmobranch organs is probably a secondary consequence of their more obvious function: detecting the electric fields of potential prey.)

Any induction system in terrestrial animals would have to depend either on measuring an induced electrical field of 10^{-9} v/m times its velocity at best, or moving a conducting loop relative to the animal's body (a flapping wing, for instance), measuring the current flow, and processing the AC sensitivity input to extract DC field strength. In fact, there is very little evidence for an induction system outside the elasmobranchs. (Even in sharks, substantial numbers of permanent magnets are associated with the lateral line organs (Kirschvink and Lowenstam, 1978a), and it may be that the magnets, insensitive as they are to electric fields, are used to correct the ampullae output for static magnetic field effects.) The best direct test for an induction system is to affix a static field to the animal and observe the consequences. Both a permanent magnet and a paramagnetic system should be affected. In pigeons, for example, the weak static field of a Helmholtz coil disrupts cloudy-day orientation (Walcott and Green, 1974) while an induction detector, which senses motion through a field, would be unaffected.

Most other terrestrial animals are said to respond to magnetic fields while moving slowly, if at all. As a result, the induction strategy seems a poor bet, and will not be discussed further in this paper.

Permanent magnets

The second of the plausible detector systems is based on the tendency of permanent magnets to align their own fields with that of the earth in the manner of compass needles. A permanent magnet detector would probably need to measure the torque generated by the interaction of these two fields (first suggested by Lowenstam, 1962). This interaction is a consequence of how permanent magnetism arises. Just as moving through a magnetic field induces current flow, so too, moving a charged particle creates a magnetic field. The ultimate source of the magnetic properties of matter is electron and orbital spin. Each electron produces a field along the axis of its spin, but most electrons exist in pairs of opposite spins which produce self-cancelling fields. Atoms with an odd number of electrons have, of necessity, a net magnetic field produced by the unpaired electrons. If the spins of the unpaired electrons are oriented randomly between atoms in a piece of matter, the fields cancel each other. If, on the other hand, the atoms with the unpaired electrons are arranged in large enough crystals with favorable atomic spacing, a stable alignment of the spins may be generated, and a strong net magnetic field produced.

Permanent magnets--the necessary prerequisite for any "compass needle" detector--have been located in several organisms, and studied extensively in four. Magnetotactic bacteria, for instance, use a chain of permanent magnets to steer themselves down the earth's field lines and into the mud (Blakemore, 1975). This orientation is entirely passive. Honey bees possess a substantial number ($\sim 10^6$) of transversely aligned permanent magnets

in the fronts of their abdomens (Gould, et al, 1978). The teeth of chitons are magnetic (Lowenstam, 1962; Kirschvink and Lowenstam 1979b). Homing pigeons have a small, unilateral, innervated piece of tissue between the brain and the skull which contains approximately 10^8 permanent magnets (Walcott, et al, in press). In each of these cases there are other closely related species in which magnets have not been observed (Kirschvink and Gould, unpub. data).

One of the most commonly occurring magnetic crystals is magnetite: Fe_3O_4 . Because of its importance to geologists in the study of paleomagnetism, its chemistry and other characteristics are well known. Magnetite is of special interest in this context because it is known to be synthesized biologically by chitons for use in their major lateral teeth (Lowenstam, 1962). Moreover, it has been identified as the major (and probably the sole) component of the magnets of bacteria (Frankel, et al, 1979), bees (Gould, et al, 1978), and pigeons (Walcott, et al, in press). This fortuitous convergence of paleo- and biomagnetism on magnetite, combined with our measurements of magnet size, permit relatively precise calculations of how sensitive presumptive detector configurations ought to be, and yield a variety of testable predictions. These models and their consequences are detailed below.

The best direct test for a permanent magnet detector is demagnetization. This approach is based on the realization that only an orderly alignment of the fields of the 10^6 - 10^8 magnets found in bees and pigeons can allow magnetic transduction, and this order can be destroyed. To demagnetize an animal, one must first know the external field strength necessary to overcome the internal stability of the strongest magnets and force them into alignment. Then, by applying an alternating field greater than this, the fields of the magnets--the unpaired, mutually aligned electron spins in the crystals--

will track the applied field back and forth. If the alternating field is slowly decreased, first the larger (more stable) and then the smaller magnets will stop being driven, retaining the alignment of the last field strong enough to realign them. The result will be a randomization of individual field directions, and deactivation of any detector. Paramagnetic materials, on the other hand, are not affected in any lasting way by alternating fields.

Demagnetization will not work on the magnetic bacteria because their magnets are stuck together in a string, and so act as a single magnet. A strong field will remagnetize them, however, and their behavior is altered accordingly (Kalmijn and Blakemore, 1978). Demagnetization has not yet been tried on pigeons. It will be interesting to discover whether either the map or the compass will be affected. In honey bees, permanent magnets look at first glance like the best bet for the circadian rhythm system, and our finding that not all bees have magnets (Gould, et al, 1978) is consistent with our observation that the rhythms of only a part of the foraging population can be affected by magnetic fields (Cullen and Gould, unpub. data). However, the orientation of the magnets is inappropriate to account for the misdirection data. For example, the transversely aligned magnets in the bees should feel the most torque when the bees dance along the earth's field lines, and yet the misdirection under these conditions is zero, and identical to what is observed at any angle in a zero field. Similarly, motion perpendicular to field lines should cause the transverse magnets to feel minimum torque, yet misdirection here is the greatest. Cancelling the earth's field--which should have little effect on the already minimized torque--causes the misdirection to disappear. For the horizontal dances, the situation is similar. In fact, demagnetized dancers show the same magnetic behavior as normal dancers (Gould, et al, in press). Demagnetization of circadian-entrained foragers

has not been tried yet.

Paramagnetism

The third detector strategy is paramagnetism--the temporary alignment of unpaired electron (and orbital) spins with any external magnetic field. The result of this alignment is that each electron acts as a local magnetic field amplifier, generating its own field which adds to the external field. The transduction of paramagnetic effects may be imagined along a variety of lines. Perhaps the most interesting possibility suggested to date is optical pumping (Leask, 1978). This system, however requires light, while none of the many magnetic effects--honey bee dances, for one--is known to suffer in the absence of light. Nevertheless, many organic molecules are paramagnetic, and paramagnetism is often invoked to account for the 45 minute "adaptation time" required for bees to respond fully to a shift in magnetic field strength (Lindauer and Martin, 1972). Although it is true that the electron spins in a paramagnetic substance, after being aligned by an external field, are randomized in a null field by thermal noise, the time course of this process is measured in nanoseconds rather than minutes.

Superparamagnetism

There is, however, a way to obtain such a long relaxation time by using crystals of a naturally magnetic material such as magnetite. Below a critical size, thermal fluctuations within a ferromagnetic domain can cause the direction of magnetism to change randomly or to align with an applied field (Neel, 1949). Like single domains, they are always magnetized fully to saturation. Depending on the crystal size, seconds, minutes, or even days may be required to change the magnetic directions in a null field. This particular type of ferromagnetic behavior is known as superparamagnetism, and the size-shape

threshold for magnetite is shown on fig. 1 (after Butler and Banerjee, 1975). This type of crystal, however, need not be imagined to explain the honey bee "adaptation time." Since the foraging bees whose dances are being monitored are spending most of that time outside the hive in the earth's field flying to and from the food, any slow-decaying superparamagnetic grains would represent a useless, jumbled, time average of all the bee's recent orientations to the earth's field. Then too, the precision of crystal size necessary to generate a halflife of 20 rather than, say, 25 minutes is on the order of $10\text{\AA}$ (fig. 1). In fact, the "adaptation time" is probably a consequence of neural processing rather than the characteristics of the detector as a strikingly similar adaptation period is seen in sun compass orientation (Gould, in review; Lindauer, 1959).

Although superparamagnetic crystals need not be employed to explain adaptation time, they represent a whole class of detector strategies not previously considered. Biomagnetic measurements are very encouraging. Honey bees, for example, are richly supplied with approximately 10^8 such crystals, and virtually all fall into the narrow size range of $300\text{--}350\text{\AA}$ (data below). Pigeons, too, have superparamagnetic crystals, but only on the side of the brain opposite the permanent magnets (Walcott, et al, in press). These intriguing measurements have also demonstrated that the crystals are composed of magnetite, making possible the relatively precise modelling discussed below.

The behavioral test for paramagnetism is by exclusion: if a static field moving with an animal disrupts its behavior, induction is ruled out; if demagnetization has no effect, permanent magnets are eliminated; and all that is left is paramagnetism. Presman (1970) concludes, however, that most ordinary paramagnetic effects on biological systems require magnetic field strengths hundreds to thousands of times stronger than that of the earth; this leaves superparamagnetism as the most likely cause. Finding that the maximum effect of a static field is associated with the anatomical concentration

of superparamagnetic crystals, however, would be very suggestive.

Because large concentrations of magnetite, both as permanent magnets and superparamagnetic crystals, have been discovered in bacteria, honey bees, and homing pigeons, we believe that a ferrimagnetic process for magnetic field reception in these animals is a strong possibility. Since magnetite is so well studied in connection with paleomagnetism, there is an exhaustive literature on its theoretical and experimental magnetic properties. Combined with the recent biomagnetic measurements and the vast literature of behavioral data, it is possible to construct a limited number of highly constrained ferrimagnetic models which make specific, testable predictions. In this paper we will review briefly what is known about the process of magnetite biosynthesis and its magnetic properties. With this basis, we will consider the two basic classes of ferrimagnetic strategies for magnetic field reception, and outline the predictions and strategies for testing each.

MAGNETITE

Biosynthesis of Magnetite

Although magnetite is found in a variety of organisms, relatively little is known about the metabolic pathway(s) by which it is formed. The mineralization sequence in Chitons (Polyplacophora) is best known because it is displayed continuously in the teeth along the radula; this process may be similar to that in other organisms (Lowenstam, 1962, 1974; Towe et al, 1963; Nesson, 1968; Towe and Lowenstam 1967; Kirschvink and Lowenstam in press). In chitons, ferric iron is first concentrated near the area to be mineralized with the iron storage protein, ferritin. Ferric iron is held in the core of the ferritin macromolecule by an approximately 60 Å subunit of the mineral ferrihydrite ($5\text{Fe}_2\text{O}_3 \cdot 9 \text{H}_2\text{O}$, Harrison, et al, 1976; Towe and Bradley, 1967; Chukrov, et al, 1972). During this buildup, an organic network forms

in those areas of the tooth which later will be mineralized. The fibrous organic material makes honeycomb-like compartments of roughly the same size as later mineralized grains ($\sim 0.1 \mu\text{m}$ in diameter). Through an as yet unresolved mechanism, the iron in an external storage reservoir is dissolved and reprecipitated again as crystalline ferrihydrite within the organic compartments. Once this organic matrix has been filled, magnetite rapidly replaces the ferrihydrite and may be seen as a sharp transition between red and black teeth along the radula. Magnetite has an inverse spinel structure with cubic close-packed oxygens, while ferrihydrite has the hematite structure with the oxygens arranged hexagonally; thus magnetite must form through the non-topotactic dissolution of the ferrihydrite (Bernal, et al, 1957). During this dissolution, $1/3$ of the iron atoms are reduced to Fe^{++} , the material is dehydrated, and the oxygens repacked. Although the agents responsible have neither been identified nor isolated, this is probably an enzyme-mediated process. Magnetite in chitons, however, is always formed from ferrihydrite and has never been found as a direct precipitate (Kirschvink and Lowenstam, in press). Ferritin may be present in magnetotactic bacteria (Frankel et al, 1979) and may also be associated with magnetite mineralization in pigeons (Walcott et al, in press).

Magnetic properties of magnetite

Magnetite is an inverse spinel. As such, the iron cations occupy two sub-lattices, one in four-fold and one in six-fold coordination with the oxygen. A super-exchange quantum mechanical coupling acts between these sites, making their atomic moments antiparallel. The numbers of Fe^{2+} and Fe^{3+} cations which occupy sites in each sublattice are not equal, however, and the difference gives rise to a type of ferromagnetic behavior known as ferrimagnetism. The bulk magnetic

properties of a ferrimagnetic material vary directly as a function of its crystal size and shape, and are illustrated for isolated parallelepipeds of magnetite on the stability diagram of Fig. 1 (after Butler and Banerjee 1975). The horizontal axis is the ratio of width to length for a given grain, while the vertical is the length. Grains which plot in the single-domain (SD) and superparamagnetic (SPM) areas are those in which a uniform, parallel magnetic spin structure exists across the entire volume of the particle. Thus, these grains are always magnetized fully to magnetite's saturation value of 480 Gauss (emu/cm^3). Single domain grains are those in which the magnetic direction is extremely stable; despite thermal agitation they can remain unchanged at room temperature through all of geologic time ($>4.5 \times 10^9$ years). In grains smaller than the bottom two lines on Fig. 1, however, thermal activation destroys the immortality of the remanence and moments from each grain tend to be randomized or preferentially aligned with local magnetic fields/ in direct proportion to their strength. For this superparamagnetic (SPM) behavior, the grains themselves do not need to move for the magnetic direction to change. Neel (1949) has shown that the characteristic relaxation time required for the magnetic direction of an isolated domain to change spontaneously is:

$$\tau \propto \exp(VMH_c/2kT) \quad (1)$$

where τ is the relaxation time, V is the grain volume, M is the magnetization, H_c is the microscopic coercivity, k and T are the Boltzman's constant and the absolute temperature, respectively. Thus, the boundary between the single domain and superparamagnetic stability fields on Fig. 1 is temperature and size dependent. Above a critical size, the one-domain state is no longer stable, and the atomic moments will not align themselves uniformly through the particle. Two or more domain configurations will form within the crystal, yielding a lower external magnetic field (multi-domain behavior). Most organic magnetites which have been reported are either SD or SPM (Gould et al, 1978;

Frankel et al, 1979; Walcott et al, in press; Kirschvink and Lowenstam, in press).

A uniformly magnetized sphere of radius a (cm) and magnetization J_s (Gauss) will produce a magnetic moment of:

$$\mu = VJ_s = \frac{4}{3} \pi a^3 J_s \text{ (emu)} . \quad (2)$$

Although the magnetic field inside the sphere is of uniform intensity, the field outside at all distances is that which would be generated by a dipole of strength μ if it were at the sphere's center. The magnetic field strength outside at a distance x along the direction of μ is therefore:

$$B(x) = \frac{2\mu}{x^3} = \frac{8}{3} \pi \frac{a^3}{x^3} J_s \text{ (Gauss)} . \quad (3)$$

(Note: Gaussian cgs units are used uniformly throughout this manuscript.)

Magnetic field 90° from the axis (at the magnetic equator) are exactly $1/2$ of this value. Note that the maximum magnetic field at the surface of any magnetite sphere is independent of the grain size ($x=a$), and has a value near 4025 Gauss (0.4025 Tesla).

PERMANENT MAGNET DETECTORS

Torque detectors

The first and simplest strategy for building a permanent magnet magnetoreceptor is to use a large number of single domain magnets aligned such that their torques add along a common axis. The strategy here is to make the grains somewhat elongate and place them together in a chain.

Demagnetizing fields generated by the shape anisotropy of a long grain will constrain the spontaneous remanence to lie along the long axis, just as a nail prefers

to magnetize along its length. Each domain of magnetic moment μ will feel a torque in the earth's magnetic field of $\mu \times B$. If every domain is magnetized parallel to its neighbors and glued to a long rod as sketched in Fig. 2, the rod as a whole will feel a torque approximately equivalent to $(\Sigma \mu) \times B$. (For example, $\sim 4 \times 10^{-13}$ dyne-cm in a magnetotactic bacterium). Each of these crystals should plot in the SD stability field of Fig. 1 so as to yield the maximum moment for a given amount of magnetite. At this stage, the rod could be connected to a mechanoreceptor such as a sensitive hair cell in a fluid-filled labyrinth or a pressure receptor (pacinian corpuscles). Virtually any sensitivity could be obtained with this structure by the simple addition of more single domain magnets. New domains, if formed at one end of the structure, would feel the effect of their nearest SD neighbor if within about $1000 \text{ \AA}$ (Fig. 3). As the new grains grew in size across the sharp SPM-SD transition of Fig. 1, they would gain a permanent magnetization parallel to the rest of the chain and the process could be repeated. The final direction of magnetic remanence is thus that of the first crystal to form; this direction, however, should parallel that of the local geomagnetic field at the time it first grew in size across the transition. In some honey bees, the stable natural magnetic remanence probably reflects the orientation of the pupae in the comb before it emerges (Gould et al, 1978); suggesting this type of process. Magnetite forms linear chains in magnetotactic bacteria which both passively torque the organism into alignment and control the polarity of each new crystal as it forms (Blakemore, 1975; Frankel et al, 1979). Pigeons have elongate single-domain magnetite which may also be involved in this type of detector (Walcott et al, in press; see also Fig. 1). For pigeons, we predict that any behavioral response from these grains should be removed by AF demagnetization.

Ball-bearing model

Another strategy for constructing a permanent magnet detector is diagrammed on Fig. 4. Here, a roughly spherical single domain grain of magnetite is positioned along a nerve membrane or at a synapse connecting two nerve fibers. If the grain and its surrounding organic matrix are loosely held, partially imbedded in a fluid mosaic membrane for example, the grain will be free to rotate into alignment with the earth's magnetic field. This rotation could be coupled to open or close conduction channels in a nerve membrane. Alternatively, the active sites of attached enzymes could either be exposed or protected from a synaptic gap, depending on the sphere's orientation. An acetylcholinase on one side of the sphere, for example, could block synaptic transmission. For this type of alignment to occur, the interaction energy ($\mu \cdot B$) of the grain with the magnetic field must be appreciably greater than kT , the thermal energy acting to randomize its orientation ($kT \approx 4.1 \times 10^{-14}$ erg at $T = 300^\circ K$). The earth's magnetic field (B) is roughly 0.5 Gauss at the surface, so magnetic moments greater than kT/B (8.2×10^{-14} emu) are required. Using eq.(2), we therefore find that the energy of a spheroidal magnetite grain of $688\text{\AA}$ diameter will just balance thermal agitation, while a diameter of $1480\text{\AA}$, corresponding to $\sim 10kT$, will show preferential alignment with the earth's field. As seen on Fig. 1, this size range is largely within the SD stability field of Butler and Banerjee (1975) implying that the grain itself must rotate. Yorke (in press) has shown that the RMS angular deviation from equilibrium due to thermal noise for similar grains is $(KT/\mu B)^{1/2}$, or about 18° for the larger grains. An organ may reduce this noise by a factor of $N^{1/2}$ if it averages the data from N separate grains. Next, we must find the rate at which these grains will move into alignment. Following the

analysis of Neurath (1964), the average angular velocity (ω) with which this sphere will rotate through 90° in response to the torque produced by the earth's field is given by

$$\omega = \frac{\mu \cdot B}{4\pi^2 \eta a^3} , \quad (4)$$

where η is the viscosity of the medium and μ, B , and a are as defined above. Thus, the $1480\text{\AA}$ particle in a 10 poise medium (like a cell membrane) will twist at an average rate of $147^\circ/\text{sec}$ until it parallels the ambient magnetic field. The response of this type of detector should then lag a small but measurable amount behind any change in the applied field. Note that the total amount of magnetite required for this scheme of detection is quite small; a few hundreds to thousands of these dendritic, axonal, or synaptic organs could make an extremely sensitive directional detector without giving the organism a measurable magnetic remanence. Commercially available SQUID magnetometers (Goree and Fuller 1976) can measure moments near 10^{-8} emu, so over 12,000 of the $1480\text{\AA}$ grains could exist in an organism before there would be any possibility of detecting a remanence produced by them. This may explain why we found no remanence in magnetically sensitive cave salamanders and newts after freezing and saturating them in strong magnetic fields (Kirschvink and Gould, unpubl. data). Detectors of this sort could also be spread uniformly throughout a given tissue, without forming a discrete cluster within a local area. Kirschvink and Lowerstam (1979a) found permanent magnetization of this sort in the tissues of embryonic sharks. Again, AF demagnetization should be effective in temporarily deactivating this organ as long as the frequency of the alternating field is much higher than the response time of the magnetite grain.

PARAMAGNETIC INTERACTIONS WITH FERRIMAGNETIC GRAINS

As shown by Figs. 3 and 5, the local environment around a magnetite sphere is characterized by high fields and steep gradients (fields < 4025 Gauss, and gradients of $-6 \text{ Gauss/\AA}$ or $6 \times 10^8 \text{ Gauss/cm}$). Neurath (1964), Valentinuzzi (1964) and Gross (1964) discuss the experimental effects of such conditions on various organisms and review the theory behind the paramagnetic effects which may be responsible, including molecular redistribution, rotational alignment of paramagnetic ellipsoids, and distortion of bond angles. Of these, rotational alignment requires fields far greater than those produced by magnetite grains, and the effects of bond angle distortion are not immediately expressed. Neither of these could account for magnetic field sensitivity in animals. Translational redistribution, however, depends upon both the field strength and the field gradient, $B \partial B / \partial x$. Next to a magnetite sphere, this product may be as high as $10^{12} \text{ Gauss}^2/\text{cm}$ (Fig. 6). For the case at hand, it is necessary to determine the change in energy for a small paramagnetic sphere when it approaches a superparamagnetic magnetite grain (the local energy well). The small spheres would cluster around the magnetite if this difference were greater than kT . Otherwise, thermal agitation would bounce them away and the density around the grain would go as $\exp(-\Delta E/kT)$. A paramagnetic substance of susceptibility K would feel a volume force acting upon it due to a magnetic field B and gradient $\partial B / \partial x$ of:

$$F = B \frac{\partial B}{\partial x} [K - K_0] \quad (\text{dynes/cm}^3) \quad , \quad (5)$$

where K_0 is the susceptibility of the surrounding medium. The energy difference we seek is the integral of $FV \partial x$ from ∞ to the point at which the grains touch ($r+a$), where r and a are the respective radii of the magnetite

and paramagnetic spheres (assuming a is small compared to r). Using eqs. (3) and (5), we find:

$$\Delta E = \int_{\infty}^{r+a} B \frac{\partial B}{\partial x} [K-K_0] V dx = - \frac{128\pi^3}{27} J_s^2 [K-K_0] \frac{a^3 r^6}{(r+a)^6} \text{ (ergs)} \quad (6)$$

Using this, the energy difference for the 60Å ferrihydrite core of a ferritin molecule ($a = 30\text{Å}$, $[K-K_0] \approx 3 \times 10^{-7}$) near a large, superparamagnetic magnetite grain ($r = 200\text{Å}$) is about 1.2×10^{-16} erg. - about 400 times less than kT . Therefore ferritin molecules will not cluster around a magnetite sphere. Larger spheres will experience a correspondingly greater force, but the total depth of the local energy will never exceed about .03 kT at room temperature. In general, we predict that paramagnetic interactions with ferrimagnetic materials are not likely to form the basis of a magneto-receptor.

SUPERPARAMAGNETIC FERRIMAGNETIC - FERRIMAGNETIC DETECTORS

Because the energy of interaction between two magnetic dipoles is far greater than that discussed above for a paramagnetic sphere, a number of ways exist in which interacting magnetic domains could be organized into a magnetoreceptor. Of particular interest are the interactions between grains which are normally superparamagnetic, and so plot in the bottom field on Fig. 1. Low temperature remanence studies indicate that honey bees possess large numbers (10^8) of SPM grains between about 300 and 350Å in diameter as shown and explained in Fig. 7. By exposing live bees to strong alternating magnetic fields (AF demagnetization), we were able to deactivate or temporarily confuse any permanent magnet detectors. After this treatment, these newly non-magnetic bees were still able to align their horizontal waggle dance to the 8 cardinal points of the magnetic compass

(Gould et al, in press). Such a demagnetization procedure would not affect a superparamagnetic detector, so it is reasonable to suggest that they are using the superparamagnetic material in this aspect of their behavior.

The two models we consider here include one based on the repulsion and attraction of adjacent magnetic grains, and the influence of a large SPM grain on several smaller ones (sympathetic "satellites").

Residual repulsion and attraction

The magnetic interaction between two neighboring superparamagnetic grains is capable of generating either attractive or repulsive forces, depending upon the orientation of their dipole moments. Because the direction of magnetization for a superparamagnetic grain is easily changed in response to an external field, the direction and intensities of the interaction forces could be made to vary as well and produce a detectable response. Fig. 8A shows the basic attraction and repulsion geometries for two adjacent magnetic moments, μ_1 and μ_2 . The force acting between them may be found by first noting that their interaction energy is

$$E = \frac{\mu_1 \cdot \mu_2 - 3(\mu_1 \cdot n)(\mu_2 \cdot n)}{x^3} \quad (\text{ergs}) , \quad (7)$$

where x is the separation between the moments and n is a dimensionless unit vector parallel to x . The force is then given by $\partial E / \partial x$, or

$$F = -3 \frac{\mu_1 \cdot \mu_1 - 3(\mu_1 \cdot n)(\mu_2 \cdot n)}{x^4} \quad (\text{dynes}) . \quad (8)$$

Note that if n is either parallel or antiparallel to μ_1 and μ_2 , the attractive or repulsive force is twice as strong as in the perpendicular case.

A simple linear geometry for this type of detector is an elastic rod with regularly-spaced grains as shown in Figs. 8B to D. Adjacent grains are

separated far enough such that the dipole field of one acting on its neighbors is less than that of the earth; each moment will then align preferentially with the external field. The configuration of 8B, with the rod perpendicular to the external field, yields grain to grain repulsion causing the rod to expand. An external field parallel to the rod (8C) will cause twice as much contraction, while zero field permits the moments to cancel or randomize, yielding perhaps a weak contraction. The particle size vs. separation diagram (Fig. 9) illustrates two constraints on the system assuming uniform size and roughly spherical grains: (1) the particle size must be below the SPM/SD transition, and (2) the field of one grain upon its neighbors must be less than 0.5 Gauss (the earth's field). Superimposed upon the diagram are curves of constant intergrain force, the values of which decrease to the lower right. The optimum grain size and spacing for this detector is that which yields the maximum force, shown on Fig. 9 by the shaded triangle; roughly 10^{-10} dyne can be generated in this fashion between adjacent grains. With 10^8 grains such as in a honey bee (Fig. 7), the maximum total force which could be generated is on the order of 10^{-2} dyne. If this could be focussed on an area $100\mu\text{m}$ square, the pressure would be 10^2 dyne/cm², within the sensitivity range of known mechanoreceptors. The ear, for example, has a threshold of 2×10^{-4} dyne/cm² at the ear drum ().

An alternate strategy for constructing an efficient residual repulsion and attraction detector would be to model it after a ferrimagnetic material (see McElhinny, 1973 or Tarling, 1971 for review). If a regular array of much more closely spaced grains were enclosed in an elastic matrix, the minimum energy of the external field would be obtained with alternate moments antiparallel as shown on Fig. 8E. A slight reduction of the size of every other grain would correspondingly reduce one set of parallel

magnetic vectors, causing the entire structure to have a net magnetic moment. Each grain is then analagous to the individual super-exchange coupled atomic moments within the crystal lattice of a ferrimagnetic material. After a fashion, this entire organelle should have 'superparamagnetic' behavior - the minimum energy for the structure would be that with the residual moment parallel to an external field. Eq. 8 and Fig. 9 implies that a spacing of $1000\text{\AA}$ between the $325\text{\AA}$ diameter SPM grains observed in bees would generate intergrain forces greater than 10^{-8} dyne; these forces yield a mechanical deformation analagous to the magnetostriction generated in ferrimagnetic materials. The pressure generated, however, is anisotropic. Along the axis of the external field, net attractive and repulsive forces are nearly balanced; the slight difference in alternating magnetic moments results in only a residual compression. Transverse to the field direction, however, the major interaction between grains is antiparallel attraction ($\uparrow\downarrow$); the organelle should therefore contract along this plane. Note that if a cubic packing arrangement is used, it will be easier to make the net magnetic moment of the organelle lie along one set of orthogonal axes, similar to the existence of a weak, magnetocrystalline anisotropy along the (1,1,1) axes of the magnetite lattice.

Because of the anisotropy, equatorial pressures generated by this cubic organelle as it rotates through a magnetic field should show a fluctuation with a 90° periodicity, perhaps accounting for the cardinal point orientation of demagnetized honey bees in their horizontal waggle dance (Gould et al, in press). Further, Martin and Lindauer (1972) have shown that the horizontal dance orientation disappears in fields greater than 5 Gauss (~ 10 times the earth's field). If the intergrain spacing for this model were $1500\text{\AA}$ with roughly $325\text{\AA}$ SPM particles, the field of one grain upon its neighbor would be roughly 5 Gauss, with intergrain forces again near 10^{-8} dyne. The

Martin and Lindauer breakdown then corresponds to all magnetic moments lining up to the applied field, saturating and deactivating the detector. This cubic array of magnetic grains could easily be arranged within the connective tissue surrounding a typical vertebrate pressure receptor. Using a model of this sort, we predict that the honey bee superparamagnetic detector has cubic symmetry with intergrain spacings on this order ($1500\text{\AA}$) and two slightly differing superparamagnetic grain sizes, perhaps near 300 and $325\text{\AA}$ in diameter.

Sympathetic satellites

An alternate strategy for making a superparamagnetic detector would be to let the local magnetic field of a large, spherical SPM grain influence the orientation and behavior of smaller, non-spherical magnetite particles scattered around it. The field of the large grain would tend to follow that of the earth, while the small grains would track that of the large. Fig. 10 illustrates this geometry for a fluid-mosaic membrane. The large magnetite grain is held in a fixed position, while a number of smaller satellite molecules with magnetite cores float around it in the surrounding membrane. Ion channels or active enzyme sites in the smaller molecules would control the permeability of the membrane or influence reaction rates in the surrounding substrate. At least three magneto-mechanical constraints must be met for this system to work: (1) the energy well around the large SPM magnetite sphere must be deeper than kT since otherwise the small molecules would not be kept close enough to be influenced by its magnetic field. (2) The small magnetite cores in the satellite molecules must have enough shape anisotropy so as to force any net magnetic moment to lie along its length in one direction or the other. If this is not the case, the moment from these small grains will follow the field of the larger SPM grain without forcing the satellite

molecule to rotate. Finally, (3) the torque felt by the magnetic moment of the satellite molecule from the field of the large grain must be enough to align it. All three of these criteria may be evaluated as follows by considering the energetics of the system.

The potential energy for two interacting dipoles is given by eq. 7, and may be used to determine the size of the local energy well. A large SPM grain $325\text{\AA}$ in diameter has a magnetic moment, μ_1 , of 8.6×10^{-15} emu. Lower limits on the satellite moment, μ_2 , are fixed when the maximum energy in eq. 7 just equals kT at a center-to-center separation of about $200\text{\AA}$, implying that $\mu_2 \geq kTx^3/2\mu_1 \approx 1.9 \times 10^{-7}$ emu. This moment corresponds to a magnetite sphere roughly $40\text{\AA}$ in diameter. Similarly, there is roughly a $3kT$ difference in energy for a $60\text{\AA}$ magnetite sphere ($\mu_2 = 5.4 \times 10^{-17}$ emu), such as might inhabit the core of a modified ferritin molecule. At a center-to-center spacing of $280\text{\AA}$ from the big grain, this energy falls to about $1kT$. Therefore, once the large SPM grains and satellite molecules have been formed, the rest of this detector can assembly itself.

Next, the shape of the magnetite core within the satellite molecule must be considered. A uniformly magnetized body has associated with it a magnetostatic energy or energy of self-demagnetization arising from its shape; a long thin rod, for example, prefers to magnetize along its length rather than perpendicular to it. If this energy difference in an applied field is greater than kT , the grain will rotate preferentially into alignment. This magnetostatic energy for an ellipsoid of volume V is given by:

$$E = \frac{1}{2} NVJ_s^2, \quad (9)$$

where N is a dimensionless demagnetizing factor along the direction of magnetization. Across a long thin rod, $N \approx 2\pi$ while along its length

$N \approx 0$. Therefore, $E > kT$ demands $V > kT/\pi J_s^2$, or $\mu_2 = VJ_s > kT/\pi J_s \approx 2.7 \times 10^{-17}$ emu. If stretched into an elongate particle, the $60\text{\AA}$ magnetite sphere mentioned above would preferentially align itself in an applied field rather than merely altering its direction of magnetization ($\mu_2 = 5.4 \times 10^{-17}$ emu is roughly $2kT$).

Finally, the satellite grains must be close enough so that their dipole-dipole interaction energy will force the moment of the smaller grain to track that of the larger. Again, this implies that the maximum ΔE from eq. 7 is greater than kT at some distance x , exactly the conditions for the energy well discussed above. Using moments calculated for the $325\text{\AA}$ and $60\text{\AA}$ spheres, this 1 kT center-to-center distance turns out to be near $280\text{\AA}$. Therefore, as the field of the large grain viscously follows that of the earth, magnetic satellite grains floating nearby in the membrane will rotate along with it, changing the membrane porosity, electrical conductivity, or metabolic reaction rates.

This particular mechanism leads to the interesting prediction of the existence of organic macromolecules similar to ferritin with magnetite instead of ferrihydrite in the core. As noted earlier, magnetite in chitons always forms directly through metabolic reduction of preexisting ferrihydrite; all that is required here is for the same reaction to occur within the core of the ferritin molecule. Experimentally, the existence of magnetite in these molecules might be checked through low temperature remanence along the lines outlined in Fig. 7. A $60\text{\AA}$ magnetite core would have single domain behavior below 1.5°K on the scale of Fig. 7. Warming through this temperature would then cause them to lose their remanence as did the grains between 300 and $350\text{\AA}$ in diameter on Fig. 7. Fischback and Anderegg (1965) have measured the shape of the iron core of horse spleen ferritin through X-ray scattering, and

conclude that under some conditions it may occur in elongate rods up to $95\text{\AA}$ in length. Conversion of these cores to magnetite via the chiton pathway would produce a molecule with the required properties.

DISCUSSION

Clearly, magnetite is a potentially efficient material to use as a transducer between the geomagnetic field and the nervous system. Both single-domain and superparamagnetic crystals can function in this capacity, and both are found naturally in large numbers in at least some magnetically sensitive animals. Although many variations are possible, we have discussed only the few models all of whose components are known to form biologically, and which could be connected easily to known sensory organs. For example, linear chains of single domain magnetite crystals (used in Fig. 2) are present inside magnetotactic bacteria (Blakemore, 1975; Frankel et al, 1979); spheroidal single-domain magnetite grains (used in Fig. 4) are found occasionally in chiton teeth (Kirschvink and Lowenstam, in press, also shown on Fig. 1); and the presence of superparamagnetic grains in bees is inferred through their magnetic properties (Fig. 7). Other suggestions stem directly from the physical properties of the materials involved, such as using the electrical conductivity of magnetite to alter nerve membrane resistance or having the ferrihydrite core of a ferritin molecule change to magnetite along the chiton pathway. We have suggested ways in which existing building blocks may be put together, or ways in which new blocks may be made from old. These models are intended to serve as testable working hypotheses to guide further research both in behavior and physiological studies. From a behavioral viewpoint, the first question to ask is whether or not the organism's response is due to either a single-

domain or superparamagnetic detector. The standard paleomagnetic technique of alternating-field demagnetization should at least temporarily deactivate a single-domain response, even if the total amount of magnetite involved is below the sensitivity of SQUID magnetometers.

As they stand, the models can account for a wide variety of behavioral responses and magnetic field sensitivities. The honey bee's waggle-dance behavior, for example, is strikingly consistent with a superparamagnetic organ along the lines of Fig. 8, D&E. A major advance, however, is in the unique ability of these models to account for the extreme sensitivity of organisms to the intensity and direction of the magnetic field. Many of these models balance thermal energy (kT) against the interaction energy between a magnetite grain and an external field (μB). Thus, the dispersion of individual crystals about their minimum energy state is a monotonic function of $\frac{kT}{\mu B}$, a relation which varies somewhat depending upon the model in question. As noted by Yorke (in press), if the nervous system integrates over the output of N independent grains, the resolution obtainable goes roughly as $\sqrt{N}$. Thus, the $\sim 10^8$ single-domain grains observed in homing pigeons (Walcott, et al, in press) would enable them to sense field changes on the order of $10^{-4} B$, or nearly 5γ (5nT)--approximately the range of dynamic effects on bees and pigeons. Such neurological averaging arrays are well known in the auditory and visual systems. The exact adaptive advantage of such extreme sensitivity is clear in the case of circadian rhythms, and might be useful for navigation as well. Further, the earth's magnetic field increases in intensity between the equator and the Poles by a factor of 2, corresponding to roughly a $1\gamma/\text{Km}$ North-South change. Over the same distance, the magnetic dip angle changes by 90° . Migratory animals equipped with this type of organ could therefore determine their position with a fair degree of accuracy, perhaps remembering the "feel" of the magnetic field near their

home or breeding grounds. The field also changes from east to west in a locally regular fashion which might also provide experienced animals with useful regional information with a similar 1 γ /km resolution. In addition, the accuracy with which animals respond to magnetic stimuli should increase with stronger fields up to the point at which the detector saturates. This seems to be the case with the horizontal waggle dance: the octamodal pattern is poorly expressed in low fields, but extremely clear in fields between 2 and 5 Gauss (oe.). Above about 5 Gauss the detector saturates. Although biogenic magnetite has not been reported in Mammals, much less from Primates, it should be noted that many of the magnetic properties displayed by human dowzers (tabulated by Rocard 1964) are consistent with a superparamagnetic detector.

CONCLUSIONS

1. Behavioral evidence argues against an induction mechanism for magnetically sensitive terrestrial animals. Even in elasmobranchs, where inductive detection seems a virtual certainty, there are hints that another, non-inductive system is involved.

2. Conventional paramagnetic interactions, even those due to the locally high magnetic fields and gradients near magnetite grains, are not likely to produce observable biomagnetic effects.

3. If coupled to the nervous systems, ferrimagnetic transducers would enable even stationary or slow-moving terrestrial organisms to detect weak directional or intensity changes in the local magnetic field at least as small as those which have been documented in behavioral studies of bees and homing pigeons.

4. Both the single-domain and superparamagnetic grains of magnetite discovered in magnetically sensitive animals could be used in this magnetic field detection. Most of the magnetite grain-grain interaction and orientation energies exceed kT, and thus can function in the presence of thermal agitation.

ACKNOWLEDGEMENTS

We thank R. B. Hargraves, K. S. Deffeyes and I. Thompson for help in the development and refinement of these ideas. This research was supported in part by NSF grant EAR78-03204 to JLK and BNS76-01653 to JLG, and forms part of the PhD thesis of JLK at Princeton University.

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Fig. 1. Magnetic stability diagram for isolated rectangular parallelepipeds of magnetite (after Butler and Banerjee 1975). Triangles, circles, and plus marks indicate the grain size range and axial ratios of magnetite crystals in three chiton (polyplacophora) species (from Kirschvink and Lowenstam, in press). Bacterial magnetite dimensions are those measured by Blakemore (1975), Frankel et. al. (1979), Blakemore et. al. (in press), and Moench and Konetzka (1989), and those for the homing pigeons are given in Walcott et. al. (in press). Similar boundaries for the Superparamagnetic / Single-Domain field have been calculated for elliptical bodies (McElhinny 1973).

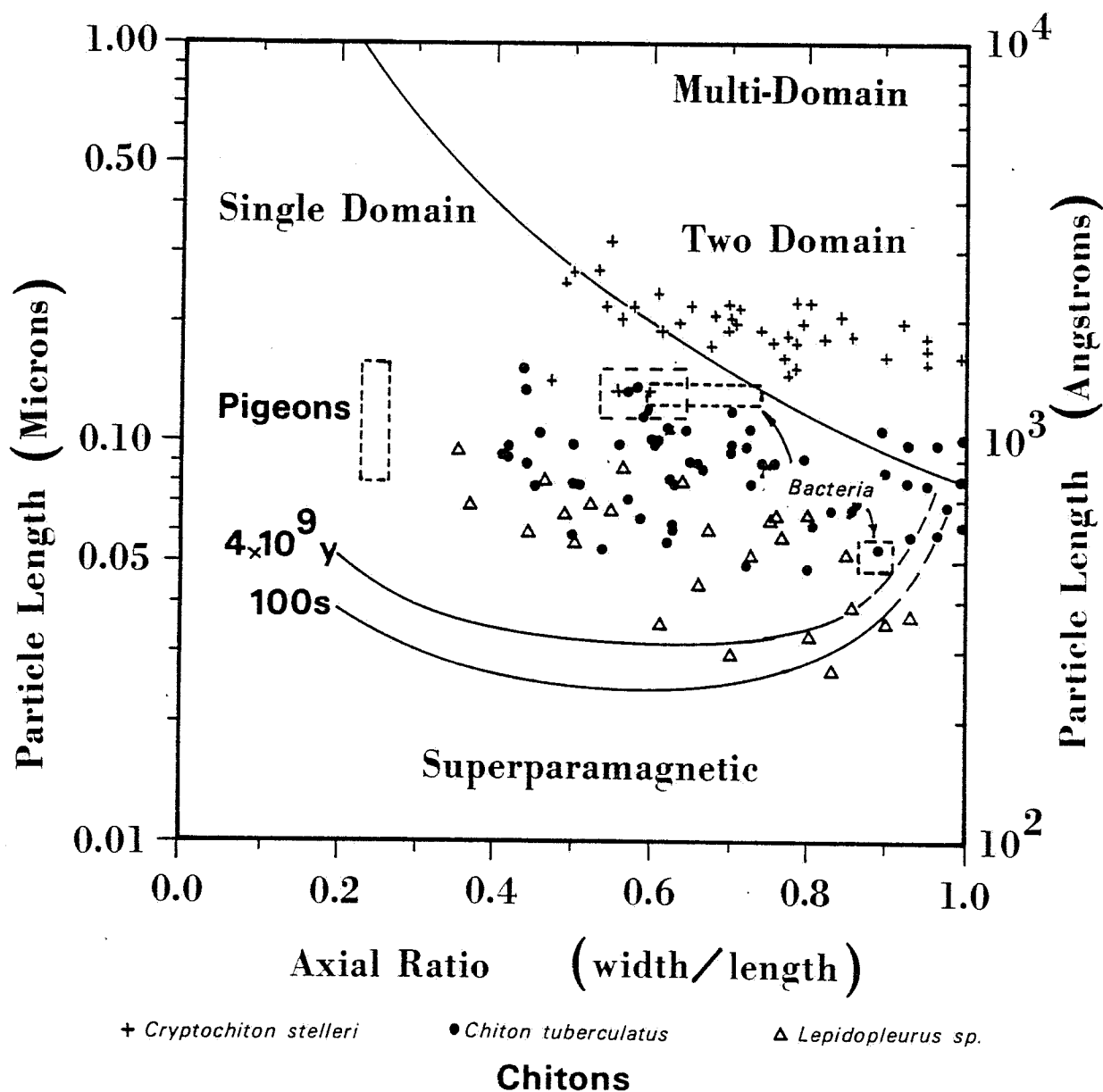


Fig. 2. Torque rod permanent magnet detector. Elongate magnetite crystals are arranged in a row with their moments pointed head-to-tail, and connected to a hair cell or some other mecanoreceptor. A new grain growing at one end will gain a permanent magnetization parallel to the chain as it grows in size through the SPM/SD transition (the blocking volume). Pigeon magnetites are of the proper shape and size for this detector (Fig. 1).

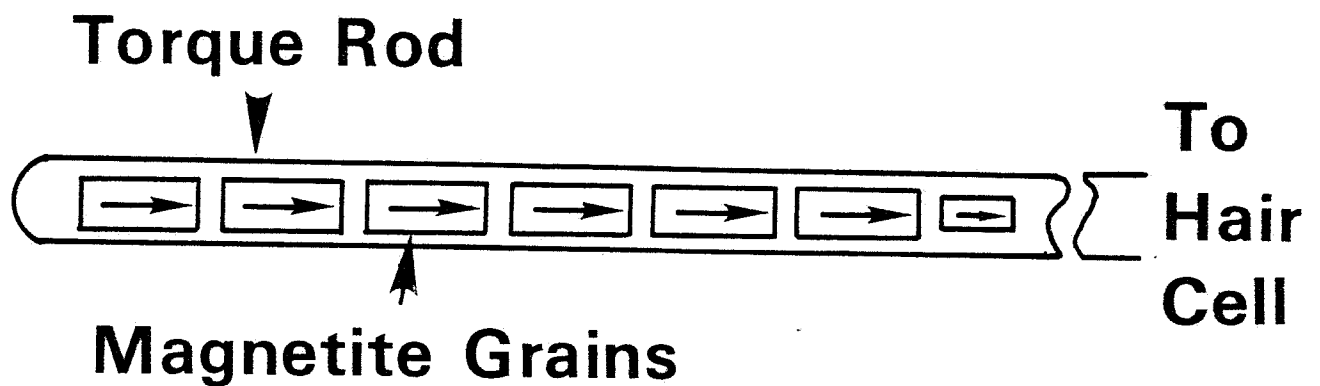


Fig. 3. Maximum magnetic field strengths near magnetite spheres (eq. 3). The grain diameter of 325Å should be superparamagnetic, the 1000Å should be single domain, and the 1600Å two domain by comparison with Fig. 1. (This latter, however, may resemble a single domain.) The maximum field at the surface of a grain is independent of the diameter and equal to about 4025 Gauss.

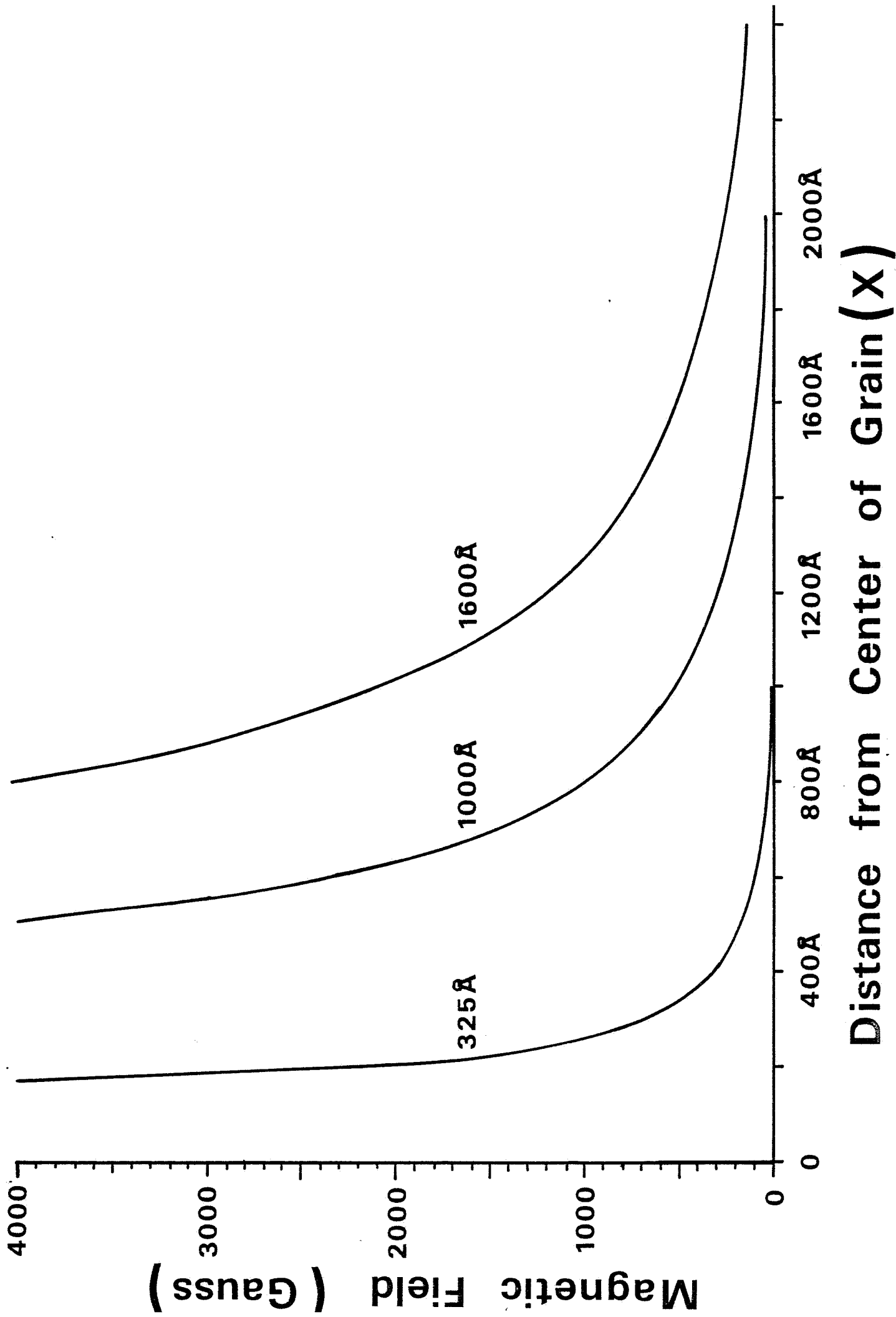


Fig. 4. Ball-bearing permanent magnet magnetoreceptor. The single domain magnetite sphere, perhaps held in a fluid-mosaic membrane as shown, will statistically align with the local magnetic field if $\mu \cdot B > kT$. (true for grains with diameters $> 688\text{\AA}$). Rotation of the grain could open or close ion diffusion gates, or permit the active sites of enzymes anchored to its surface to have access to the proper substrate. Other possible mechanisms include enzymatic inhibition or stimulation of synapse activity, or, since magnetite is an electrical conductor, changing the electrical resistance of a membrane. This latter mechanism, however, would require the partial removal of some of the organic matrix which should surround these grains (Towe and Lowenstam 1967).

**Single - Domain
Magnetic Sphere**

Ion Hole

Membrane

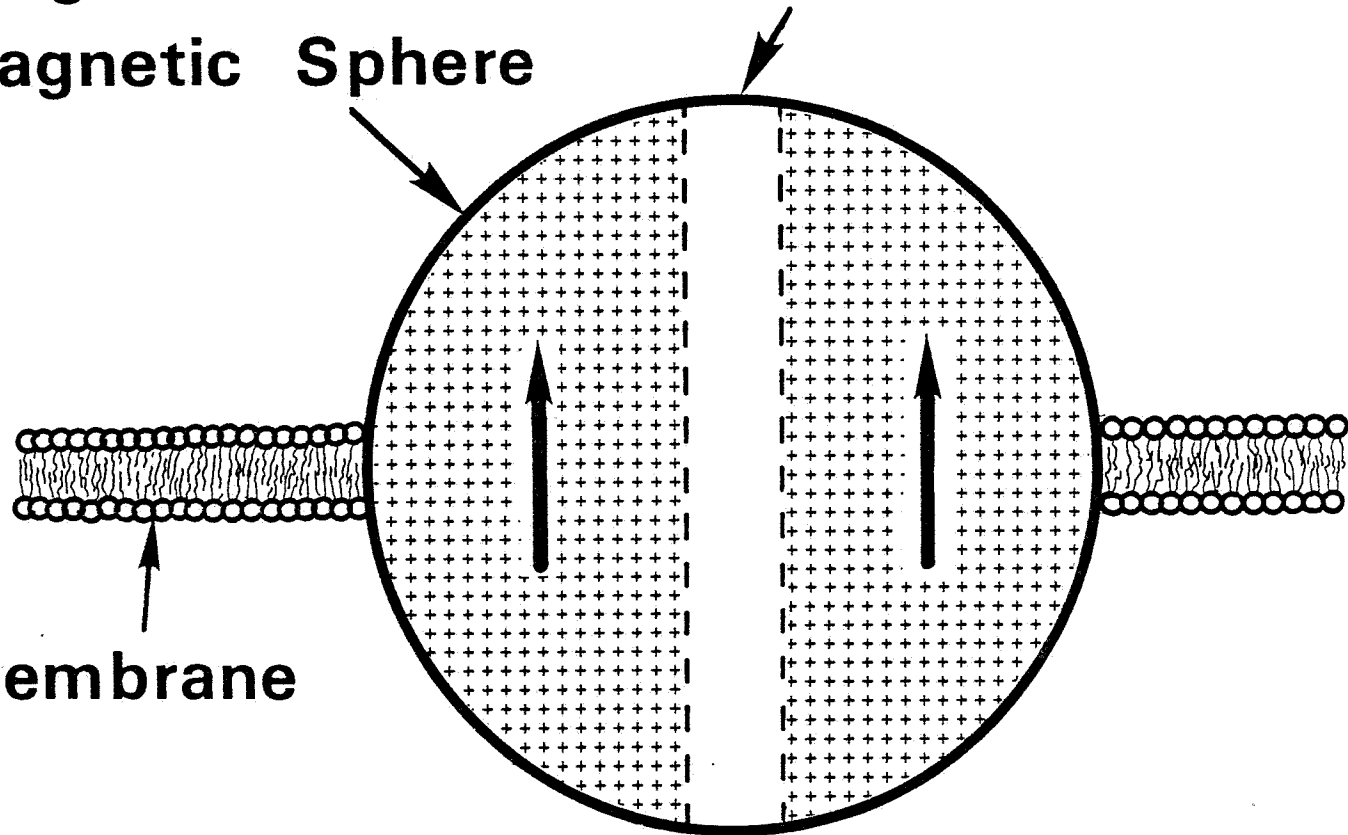
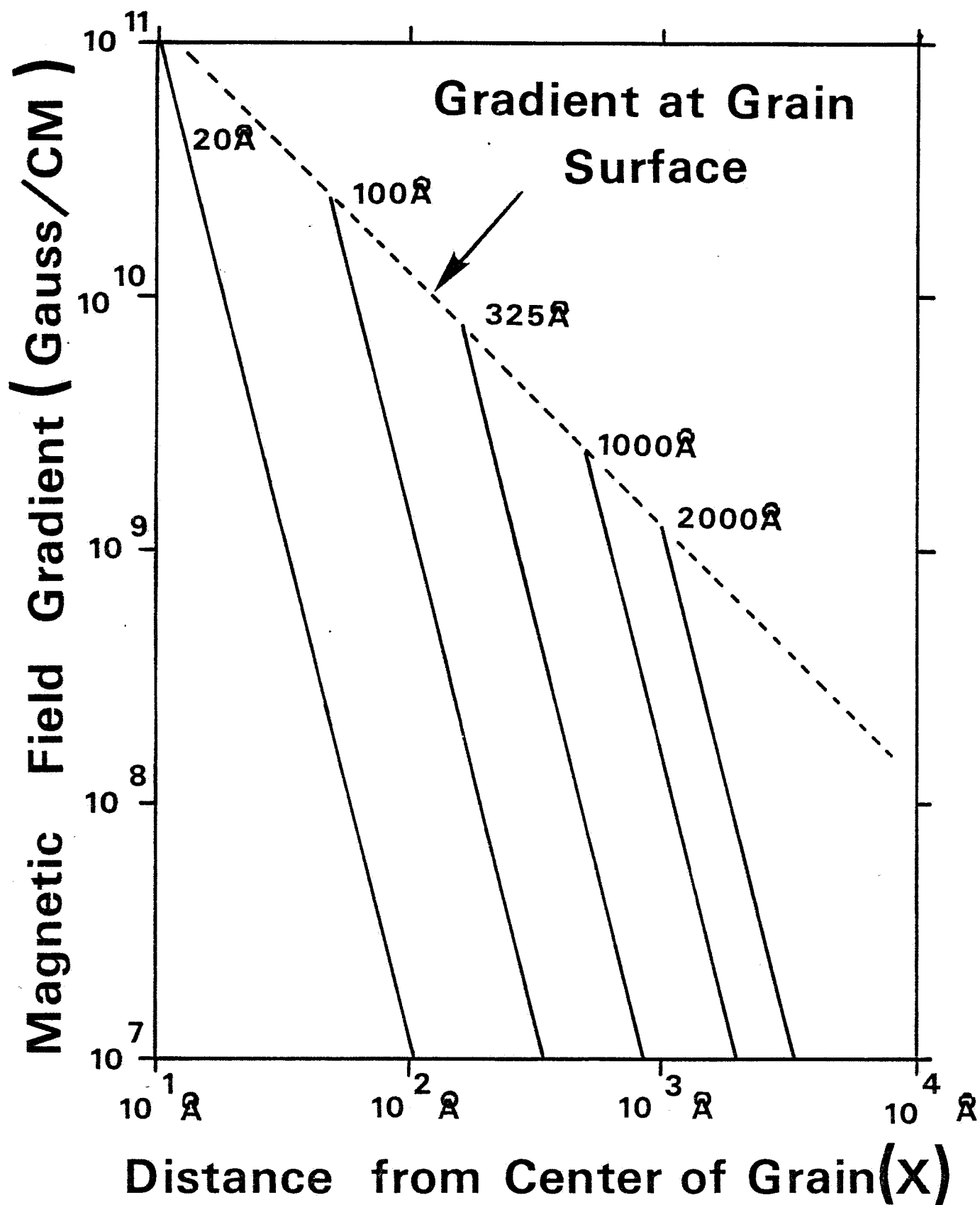


Fig. 5. Magnetic field gradient ($\partial B/\partial x$) as a function of distance from the grain surface. Each solid line indicates this relationship for the indicated grain diameter. Small grains have a much higher surface gradient than larger ones as indicated by the dashed line.

Fig. 6. Maximum paramagnetic strength near magnetite spheres. The product of the field strength (B) and its gradient ($\partial B/\partial x$) largely determines the force exerted on an adjacent paramagnetic molecule (eq. 5). Each solid line represents this function for spheres of the indicated diameter.



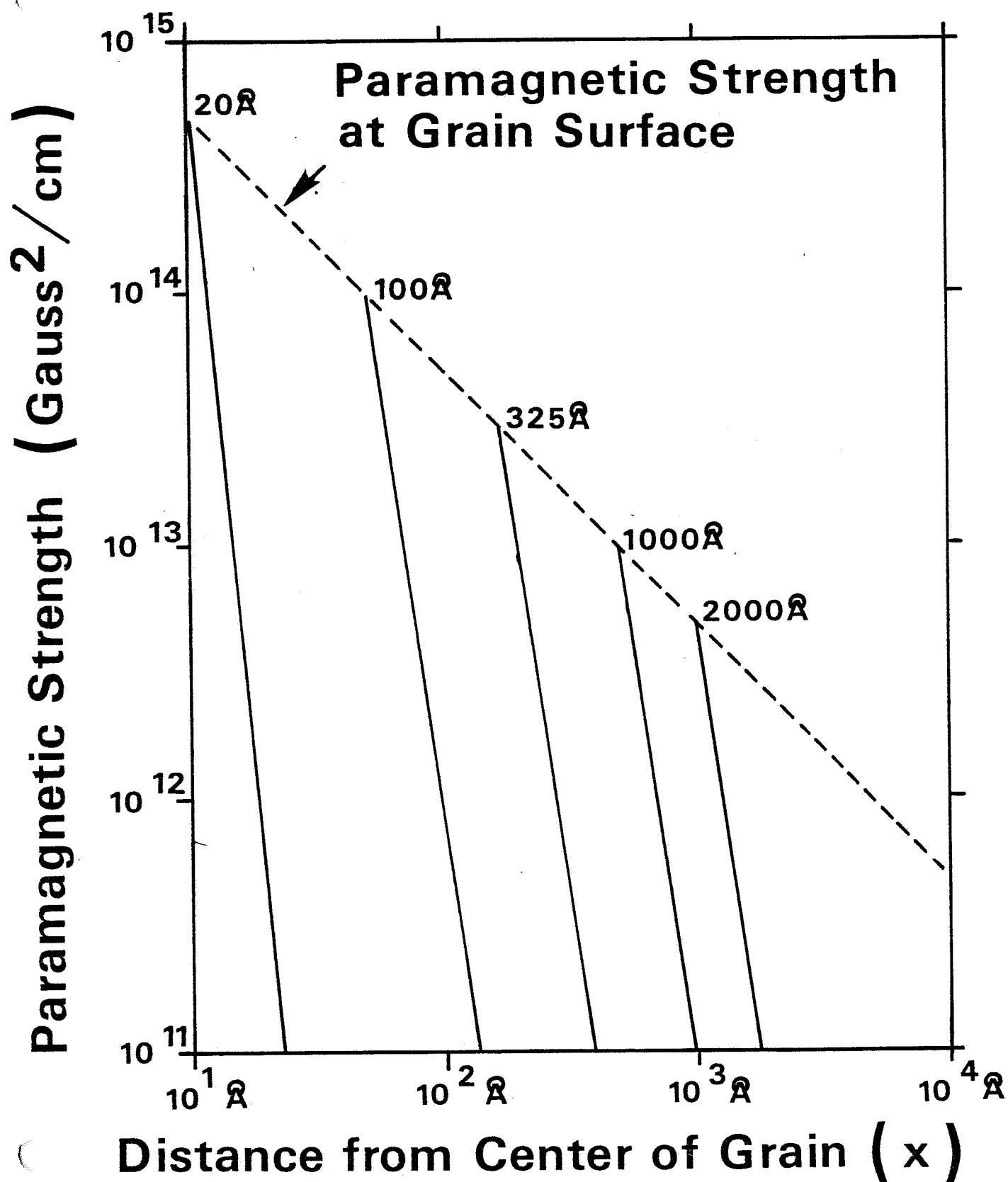


Fig. 7. Superparamagnetic grains in a worker bee. Neel's relationship (eq. 1) indicates that the relaxation time, τ , for a magnetic domain will increase exponentially as the temperature is lowered. Thus, some grains which are superparamagnetic at room temperature ($\sim 300^\circ\text{K}$) will behave as single domains capable of holding remanence at liquid nitrogen temperature ($\sim 77^\circ\text{K}$). Conversely, any net remanence held by these domains at low temperature will disappear as they warm in field-free space across their SPM/SD transition (their blocking temperature). The temperature at which the remanence is lost indicates the grain size responsible. If the material is magnetite, a nearly spherical grain $350\text{\AA}$ in diameter is close to the SPM/SD transition on Fig. 1; eq. 1 may then be used with this to calibrate the grain diameter vs. temperature along the horizontal axis. To check for superparamagnetic grains, the bee was first cooled to 77°K in the presence of a strong magnetic field (~ 3000 Gauss), forcing all the moments from SD grains into alignment. Curve 1 shows the remanence of the bee as it warmed up inside the field-free region of a cryogenic magnetometer (Goree and Fuller 1976). Most of the remanence is lost as the SD/SPM transition goes from 300 to $350\text{\AA}$. A magnetite sphere $325\text{\AA}$ in diameter has a moment of about 8.6×10^{-15} emu, so about 2×10^8 of them are necessary to account for the lost remanence. Curves 2 and 3 show subsequent warming cycles without exposure to the strong magnet.

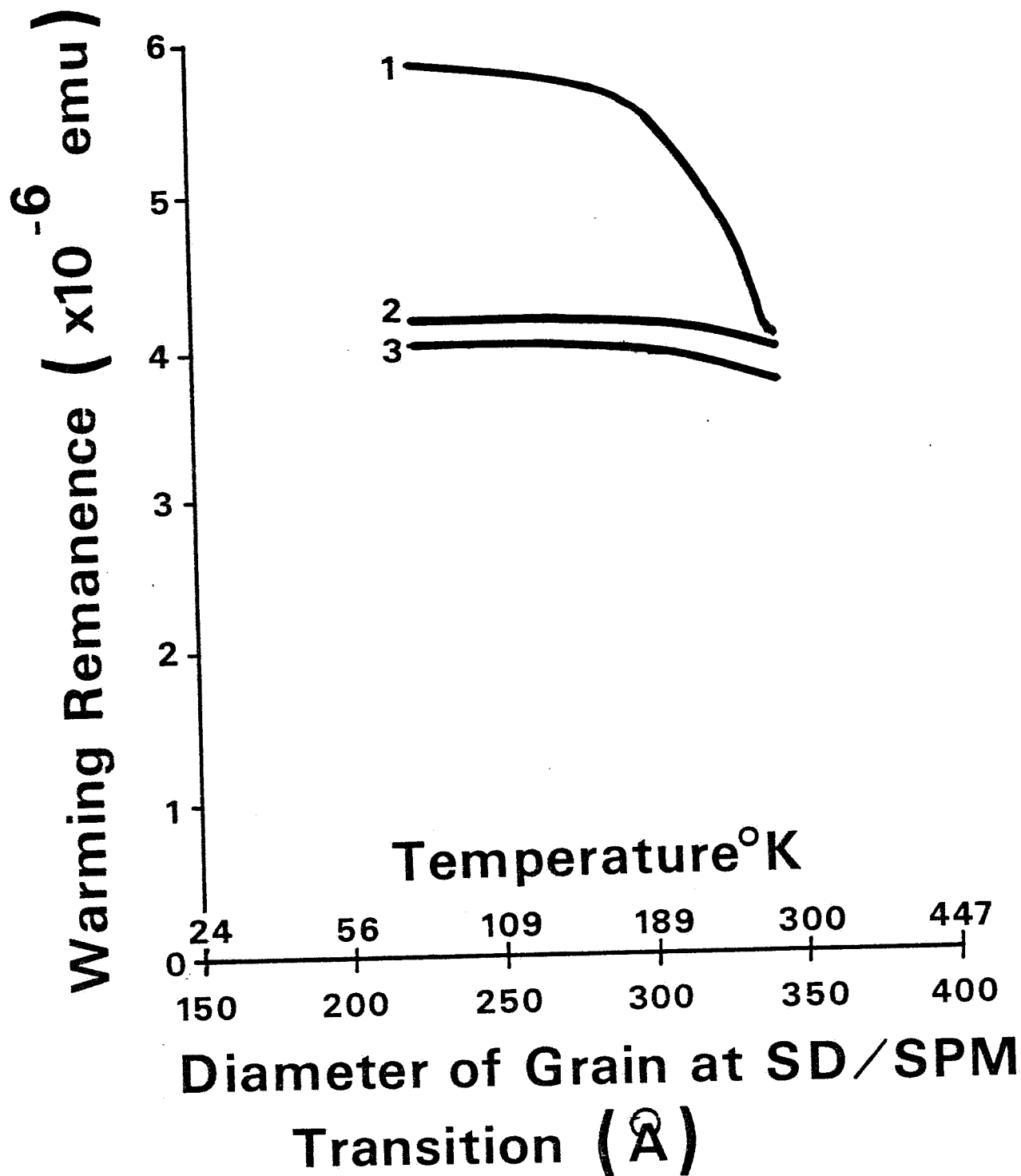
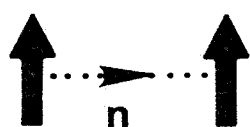


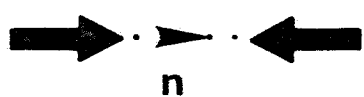
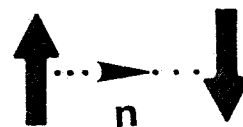
Fig. 8. Repulsion and attraction magnetic field detectors. A. Weak and strong repulsion geometries for two magnetic moments. B. to D., Elastic rod transducer. In B, the external field aligns all superparamagnetic moments transverse to the rod; they repel and its length increases. Alignment of the moments parallel to the rod as in C makes the grains attract, causing the rod to shrink. In the absence of an external field (D), the moments either randomize or pair ($\uparrow\uparrow$) so as to reduce any external field; possibly a weak contraction results. Two configurations for a ferrimagnetic analogue transducer discussed in the text are shown in E and F. Moments in E parallel the cubic 'lattice' and thus lie along the magnetically hard direction, while those in F are similarly / the easy direction.

Repulsion

Attraction



Weak
(F)

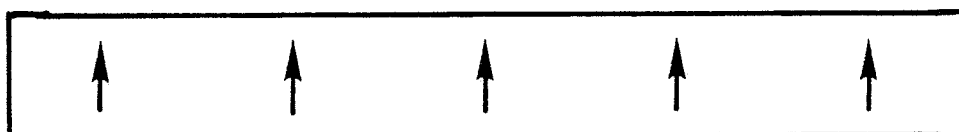


Strong
(2F)



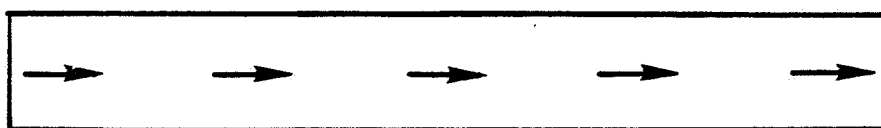
A

B



$\uparrow B_{\text{ext}}$ Expansion
 $\longleftrightarrow$

C



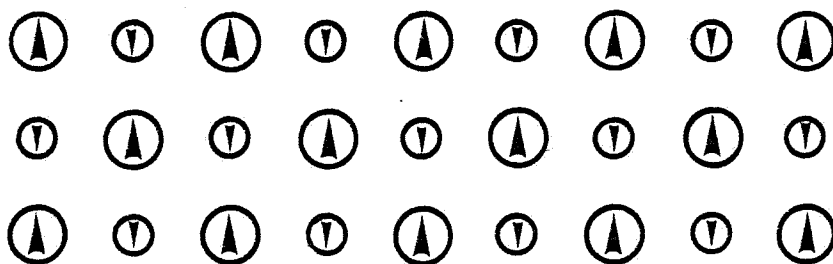
$\rightarrow B_{\text{ext}}$ Contraction
 $\rightarrow \leftarrow$

D



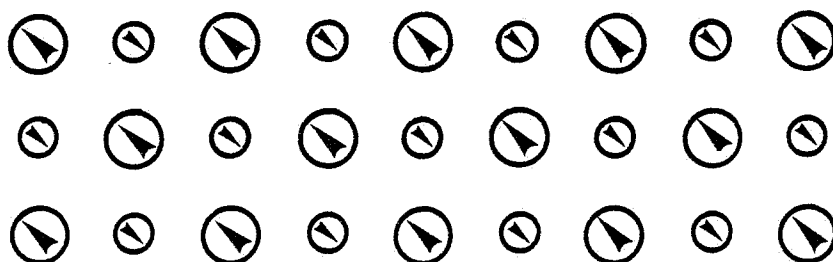
no ext B Weak Contraction

E



$\uparrow$ Net Moment

F



$\swarrow$ Net Moment

Fig. 9. Interaction force and magnetic field relationships for two SPM magnetite spheres. Both grains are of equal radius (vertical axis). Solid lines indicate grain size vs. separation which yielded constant field strength, the dashed lines show constant interaction force. The best separation and grain size to use in the detector of Fig. 8B-D is just below the SD/SPM transition ($r \approx 200\text{\AA}$) and far enough apart so that the Earth's field dominates ($\sim 4000\text{\AA}$ apart.) The maximum intergrain force obtainable with this configuration is 10^{-21} of a dyne, suggesting that this is not a very good way to build a transducer.

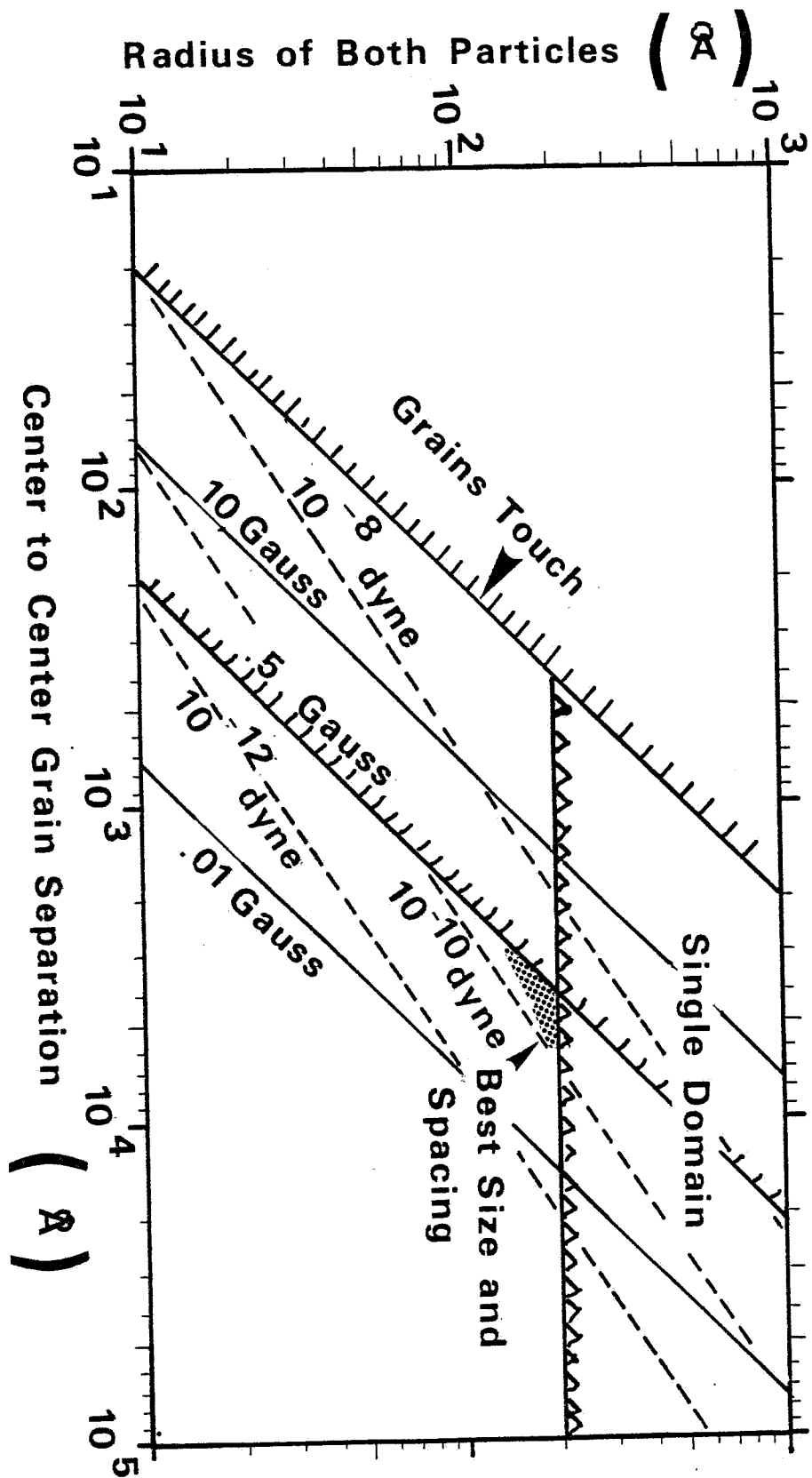
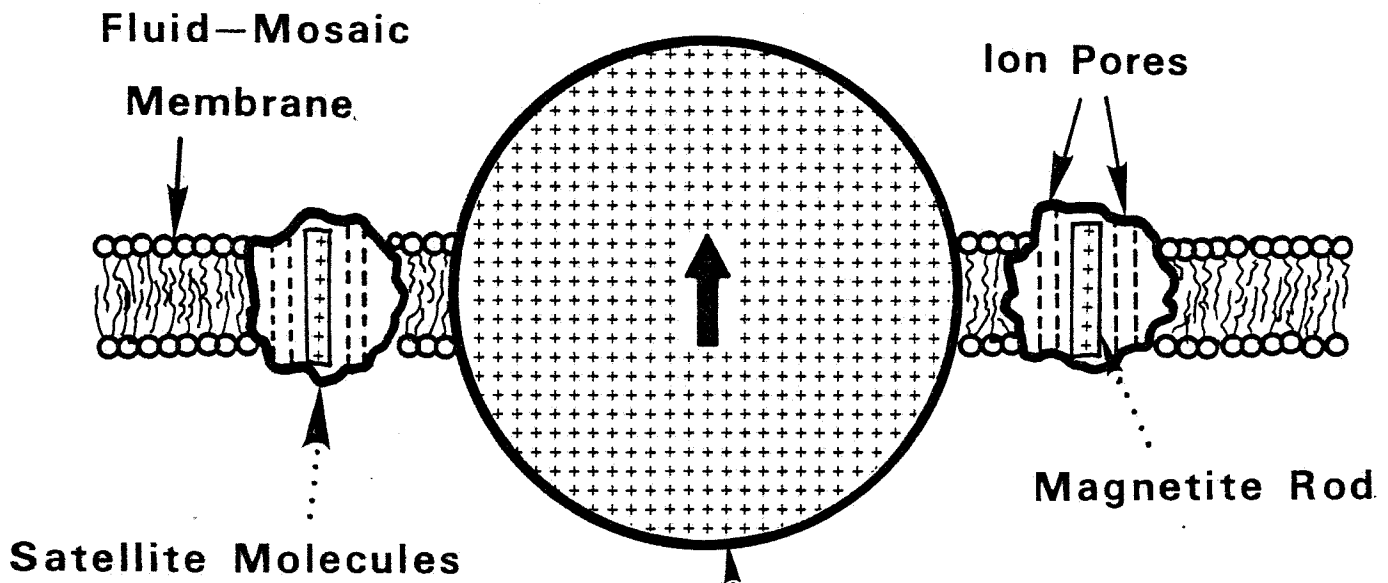
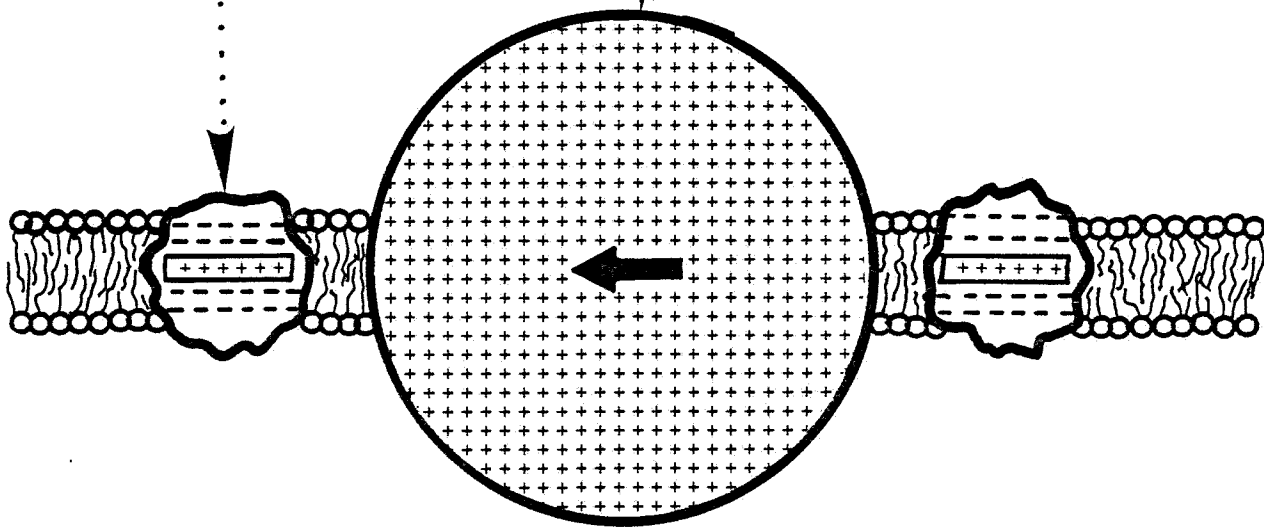


Fig. 10. Sympathetic satellites. The magnetite spheres are superparamagnetic and will statistically align their moments parallel to an external field. Satellite molecules in the surrounding membrane have a magnetite rod in their core, and will align themselves parallel to the local field lines generated by the larger sphere. Top diagram: the external field is perpendicular to the membrane, and ion pores (or active sites) are exposed to the external medium generating a porous membrane. Bottom diagram: the external field is in the plane of the membrane, blocking the pores (or active sites).

Open



Closed



Bees Have Magnetic Remanence

James L. Gould, J. L. Kirschvink and K. S. Deffeyes

same material increases linearly with the applied field until saturation is reached at about 1.8×10^3 Oersteds. The presence of magnetite in three live bees was tested by freezing them to -196°C in liquid nitrogen, and then continually monitoring the remanence as they warmed up through the isotropic point of magnetite (-143°C). In each case, the remanence decreased slightly near this temperature, indicating the presence of magnetite (19). Regardless of what these attempts to characterize the magnets produce, only our behavioral experiments can establish whether or not bees actually use these magnetic crystals for orientation.

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5. M. L. Brines, thesis, Rockefeller University (1978).
6. M. Lindauer, *Proc. Intern. Congr. Entomol. 15th* (1977), p. 450; the evidence is intriguing but indirect.
7. M. L. Kreithen and W. T. Keeton, *J. Comp. Physiol.* **91**, 355 (1974).
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12. W. S. Goree and M. Fuller, *Rev. Geophys. Space Phys.* **14**, 591 (1967).
13. We have traced the induced remanence to small ($200\ \mu\text{m}$) dark specks, which are widely distributed in the digestive tract of older bees. Under the scanning electron microscope, one class of these objects has been identified as inorganic. The other class is still being investigated.
14. We are reminded of D. Griffin's remark in a similar context that "if they do not use it, perhaps they ought to try."
15. K. M. Towe and H. A. Lowenstam, *J. Ultrastruct. Res.* **17**, 1 (1967).
16. R. F. Butler and S. K. Banerjee, *J. Geophys. Res.* **80**, 4049 (1975).
17. This is consistent with our measurements of increased induced remanence at very low temperatures, indicating that superparamagnetic domains have become stable. This is also consistent with the transverse field orientation data, since, in that orientation, only superparamagnetic crystals can easily be arranged to construct a hypothetical detector which could explain the dance misdirection data.
18. For example, the concentration of iron in nectar [M. Shabanov and N. Ibrishimov, *Acta Microbiol. Virol. Immunol.* **2**, 105 (1975)] and pollen [M. H. Hadak and M. C. Tanguary, *Tech. Bull. Minn. Agr. Exp. Sta. No. 160* (1943), p. 23] depends on the species of plants in bloom. The iron content of honey, for example, varies from 0 to 45 ppm. Without enough iron in the diet, bees could not synthesize the crystals. Alternatively, like first-flight pigeons which cannot use magnetic field information when raised in sunny areas [W. T. Keeton, *Sci. Am.* **231** (No. 6), 96 (1974)], perhaps bees do not build detectors when they do not need them. This is consistent with the observation that bees in horizontal hives do not begin orienting their dances to magnetic fields for several weeks. Since the average life-span of a forager is 3 weeks, these could easily be, and probably are, a new generation of bees.
19. M. Ozima, M. Ozima, S. Akimoto, *J. Geomagn. Geoelectr.* **16**, 165 (1964); S. Levi and R. T. Merrill, *J. Geophys. Res.* **83**, 309 (1978).
20. A preliminary survey of 18 species of invertebrates revealed natural remanences larger than 0.5×10^{-6} emu (against a background of 0.02×10^{-6} emu) in a Vespid wasp, housefly (*Musca domestica*), roach (*Periplaneta americana*), and staghorn beetle (*Passalus cornutus*), as well as a marginal remanence in a *Tenebrio* beetle. We thank T. C. Onstott and N. Dorety for making preliminary measurements, as well as the director (D. P. Elston) and staff (S. L. Bressler and M. E. Puruckner) at the U.S. Geological Survey Paleomagnetism Laboratory in Flagstaff, Ariz., for help and interdisciplinary enthusiasm. Supported by NSF grant BNS 76-01653A02 to J.L.G.

4 April 1978; revised 26 June 1978

Walcott, et. al.

PIGEONS HAVE MAGNETS

(Revised 4 April 1979)

ABSTRACT

Research on pigeon homing strongly suggests that magnetic field information is used for orientation.

The ability of pigeons to sense magnetic fields may be associated with a small, unilateral structure between the brain and the skull which contains magnetite in what appears to be single domains.

Many homing pigeons are able to find their way home after being released at an unfamiliar site. They typically take up an appropriate homeward flight direction shortly after release. To do this, the birds must know where they are with respect to home and be able to judge direction - that is, they must have both a "map" and a "compass sense"¹. On sunny days, their compass appear to depend upon the sun since clock-shift experiments predictably deflect departure bearings². Since the same clock-shifted pigeons depart directly toward home on cloudy days, some non-solar backup compass must be available³. Because the ability of pigeons to orient on cloudy days is disrupted when small magnets⁴ or paired coils⁵ generating a magnetic field are affixed to their heads, it seems likely that the backup compass is partly or wholly magnetic, and is located in the head or neck. Since the initial homeward orientation of pigeons on sunny days is slightly affected by paired coils⁶ and magnetic storms⁷, and can be virtually abolished when the birds are released at strong magnetic anomalies⁸, it is possible that the sunny-day compass has a magnetic component or that the mysterious "map" system may utilize magnetic field information.

Very little is known about how pigeons might sense the earth's field. However, we know of only three general strategies which an organism might use to detect magnetic direction. One method would be to measure the electric field (ie, charge separation) generated by moving a conductor through a magnetic field. This is almost certainly the system employed by elasmobranch fishes¹⁰. Since the weak, static field of a set of coils attached to (and hence moving with) a pigeon nevertheless disrupts cloudy-day homing⁵, the compass probably does not involve an induction detector. A second possibility would be to use permanent magnets, perhaps by measuring the torque generated as they attempt to twist into alignment with the earth's field¹¹. Chitons¹², Honey bees⁹, and many species of mud bacteria¹³ do possess single domains (tiny unit magnets) of magnetite which excepting chitons, may be used for magnetic field orientation. The third strategy

might be to sense the effects of paramagnetic fields which are produced by many substances as a result of a temporary alignment of the spins of their unpaired electrons with an external field. Many organic molecules are weakly paramagnetic, and in addition, honey bees possess large numbers of superparamagnetic crystals of magnetite⁹ which are too small to have stable, permanent fields of their own at room temperature, and so behave like paramagnetic substances. In an earth's field, superparamagnetic crystals would align their own fields with the Earth's. Depending on the crystal spacing and relative orientation, these superparamagnetic domains would attract or repel each other in a way which could specify the direction of the earth's field^{11,15}.

We tested for stable and superparamagnetic domains in pigeons with a SQUID magnetometer¹⁶. Since the paired coil experiments indicate that the compass is in the head or neck⁵, we dissected approximately two dozen fresh, previously frozen, or perfused pigeon heads and necks with non-magnetic tools and looked for any natural remanence inducible at room temperature with either a 700 or 2000 Gauss magnet (a test for stable permanent magnetism), and any inducible remanence when the head and neck sections were chilled to -196°C in liquid nitrogen (a test for superparamagnetic domains in the 200-400 $^{\circ}$ size range)¹². When remanence was found, the sample was progressively subdivided until the site of magnetic activity was located.

In each of the pigeons tested we found naturally, i.e. permanently, magnetic material. The material was always unilateral and was located either in a small (1 x 2mm) piece of tissue between the dura and the skull or was too closely associated with the skull to be separated from it conveniently. About 40% of the pigeons had a natural remanence - a net field due to a preferential direction of alignment among the many individual magnets - which ranged from 10^{-7} to 10^{-6} emu, while all had an inducible remanence - a measure of the total amount of magnetic material -

of 10^{-6} to 10^{-5} emu. The relatively weaker natural remanence and other the alignment observations suggest that among the single-domain magnets is only locally regular.

We froze the naturally magnetic tissues in liquid nitrogen and induced a remanence with a 3000 Gauss magnet and then watched the remanence decay as the sample warmed up to room temperature. We observed no abrupt decrease in remanence indicating that the tissue contains few, if any, superparamagnetic domains. Honey bees, on the other hand, possess a very large superparamagnetic component.⁹ We examined the rest of the pigeon head and neck for superparamagnetic domains and found small amounts of remanence only in the half of the head opposite the permanently magnetic material.

We have also examined the tissue in a very preliminary way with both the light and electron microscope. The tissue contains nerve fibers¹³ and connective tissue and is richly supplied with clusters of electron dense structures approximately 0.08 to 0.15 μ long and with approximately a 4:1 length to width ratio dimensions which would yield stable single domains if composed of magnetite¹⁷ or maghaemite, but superparamagnetic domains if they were crystals of any of a number of other naturally magnetic substances such as haematite¹⁸. If the material is magnetite, this crystal size and the magnitude of the inducible remanence means that approximately 10^7 - 10^8 single - domain magnets are present. An electron probe analysis revealed that these particles are rich in iron, the primary component of most magnetic materials. Small but measurable amounts of nickel, copper, zinc, and lead were also detected. Similar trace elements have been found previously in magnetite crystals which are synthesized by chitons¹⁹. An x-ray analysis confirms the presence of iron.²⁰

Given the strength of the remanence and the absence of other elements, the magnetic material must be either magnetite or maghaemite (or both). To distinguish between these two minerals we removed and pooled the magnetic tissues from 5 pigeons

to obtain a Curie temperature. The remanence of maghaemite disappears between 300 to 400°C as maghaemite inverts to the weakly magnetic material haematite. The remanence of haematite in turn is lost at 680°C. The remanence of magnetite, on the other hand, disappears at about 580°C. We measure a Curie point for the pigeon tissue of $575 \pm 10^\circ\text{C}$. In addition we examined the crystals under the light microscope. Maghaemite crystals are orange while of all magnetic minerals only magnetite is black. This is because the octahedral exchange coupling in magnetite absorbs photons of almost any energy level. Although the crystals in the pigeon tissue are too small to produce a color individually, the aggregations can and are unambiguously black. We conclude, therefore, that the primary magnetic component is magnetite.

The tissues also contain an easily shattered yellow crystal about 6 μ in diameter. Similar crystals can be formed by the iron storage protein ferritin which may be involved in the synthesis of magnetite²¹. Such a crystal would have no remanence and would contain sufficient iron to synthesize approximately 2×10^5 domains of magnetite. Electron diffraction analysis now under way will establish this crystal's identity conclusively. Given its color, the total measured remanence, and the Curie temperature measurements, however, we see no way this yellow crystal could by itself account for more than a tiny fraction of the magnetic properties of this tissue.

These results do not prove that pigeons actually use the innervated, magnetite rich, naturally magnetic structure reported here as a magnetic field detector. Only the behavioral and physiological experiments now in progress can actually determine whether or not pigeons use this presumptive detector in either their "map" or compass systems, and if so, how²².

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Magnetic field sensitivity:
behavioral evidence for a super-paramagnetic detector in honey bees

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Abstract

Honey bees orient to the earth's magnetic field and possess well-oriented permanent magnets^{and} super-paramagnetic domains. When bees are demagnetized their ability to orient on a horizontal surface to the earth's field remains intact. This suggests that bees are using their super-paramagnetic crystals as magnetic field detectors.

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Although the orientation of a variety of animals is affected by the earth's magnetic field,¹ almost nothing is known about how terrestrial animals detect it. There are at least three general mechanisms which might be used². The first requires that animals possess a device to measure the charge separation which is induced when it is moved through the earth's field. A second method of detection might be accomplished by using permanent magnets which, like compass needles, produce a measurable torque as they attempt to twist into alignment with the earth's field. The third mechanism would require that animals have paramagnetic substances--molecules which, in the presence of an external field, produce additional magnetism parallel to the external field. An important variant of this hypothesis proposes that animals possess super-paramagnetic domains--tiny, ferromagnetic crystals which easily align their magnetism in the direction of the applied field at room temperature.

Honey bees are sensitive to the earth's magnetic field. For example, normal dances on vertical comb show small errors in direction (missweisung) which depend on the orientation of the earth's field³. When a hive is left on its side for at least two weeks, the resulting horizontal dances (in the absence of other cues) become oriented to the eight points of the magnetic compass⁴. Both of these effects disappear when the earth's field is cancelled.

We reported previously that honey bees possess transversely-aligned stable and super-paramagnetic domains of magnetite². In the process of characterizing these magnetic crystals, we measured their saturation magnetization--the external field strength required to align all of the domains. We found that the number of domains realigned increased steadily with increasing applied field strength until complete saturation was reached

at 1800 Oe.--approximately 3600 times the strength of the earth's field. This measurement provides the information necessary to test the permanent magnet hypothesis. If the normally transversely-aligned domains were to have their orientations randomized, a permanent magnet detector would be deactivated. Saturation and randomization should have no effect on either an inductive or (super-)paramagnetic system.

In order to demagnetize a bee, it is necessary to put it into an alternating field (AF) of at least 1800 Oe. so as to force the magnetism of all the domains to track the applied field, and then to decrease the field strength slowly so that first the stronger, and then ever weaker domains stop tracking the AF field. The result, assuming that there is no bias from a DC-field, is that the domains stop being driven one by one, and come to rest in a stable orientation determined by the polarity of the last external field strong enough to reverse them. Hence, their directions become randomly dispersed in space and no net magnetism results.

We used a 2100 Oe. coil tuned to 60Hz⁵ to demagnetize our bees, and mounted it inside a 10-coil Helmholtz system⁶ to cancel the earth's field and thereby prevent any DC bias on the domains as they came to rest. Bees on their way out of the hive would walk into the coil, spiral through 360°, and then walk out of the coil and into a large null field (10^{-4} Oe.). The wide, even distribution of domain sizes inferred from the Curie temperature curve² assured that no more than 0.2% of the domains would ever drop out in any single field cycle, with the result that the demagnetizing process was free of any discontinuities which might have tended to bias the net domain orientation. We confirmed that the demagnetization worked by measuring 6 of the treated bees in a cryogenic magnetometer⁷. The mean remanence was 0.01×10^{-6} emu (against a background of 0.01×10^{-6} emu) compared to a remanence of 0.34×10^{-6} emu measured in untreated bees from the same colony.

The assay for magnetic field sensitivity we used was the orientation of horizontal dances in a non-magnetic hive which had been on its side for four weeks. We trained individually numbered foragers to a station 240 m away, and video taped their dances under red light (to which bees are blind). Bees which showed good orientation to the earth's field (Fig. 1a) were then selectively demagnetized as they left the hive. Their dances were taped on each subsequent return from the feeder (Fig. 1b).

Demagnetization had no effect on the ability of bees to orient to the earth's field in this context. We conclude, therefore, that bees do not employ a permanent magnet detector in their horizontal dance orientation. These results reinforce our suspicion that bees possess a super-paramagnetic detector. We base this guess on two other observations. First, some bees possess only super-paramagnetic domains², implying that permanent domains may not be necessary, and could in fact represent crystals which simply became too large during development. Second, the missweisung effect of the earth's field on vertical dances cannot be accounted for easily with transversely-aligned permanent domains. This is because missweisung disappears when bees dance along field lines³. In these dances, the fields of the domains would be orthogonal to the earth's field, the orientation which would cause maximum torque on the magnets. Yet a null field which must result in no torque, also causes missweisung to disappear. It is difficult to understand how both a maximum and minimum detector response could produce the same behavioral output. More puzzling still, bees dancing perpendicular to the earth's field lines would have little or no torque on their magnets--a situation similar to the null field circumstance--and yet display maximum missweisung³.

Super-paramagnetic domains, on the other hand, could be arranged to

mimic the missweisung behaviour in many ways. Suppose, for example, the crystals were anisotropic with their long axes transversely oriented. Assume further that they were spaced close enough to interact with each other and were arranged around, say, a pressure sensor. With the field transverse to the bee (the maximum missweisung condition), the long axis of the crystals would be aligned with the field, and a maximum paramagnetic field would be induced. In this instance the super-paramagnetic crystals would repel each other, creating an effect on the pressure sensor which would disappear in a null field. This is consistent with the behavioral data. When such a bee faces along the field lines such that the axis of its super-paramagnetic crystals would be perpendicular to the earth's field, a minimum paramagnetic field would be induced, and cancelling the external field would have little or no effect. Again, this mimics the observed behavior. Other models are possible, including ones which do not assume any shape anisotropy⁸. With this in mind, we are now attempting to test the super-paramagnetic hypothesis⁹.

Although these data indicate that bees are using a super-paramagnetic detector strategy in their dance orientations, they say nothing about the sensory mechanisms which must underlie their reported ability to set their circadian rhythms to small regular daily variations in the earth's magnetic field⁴. Indeed, such an ability is more plausibly accounted for by a permanent domain detector, and it may be that bees have two systems for extracting magnetic field information. Experiments are underway to test this possibility.

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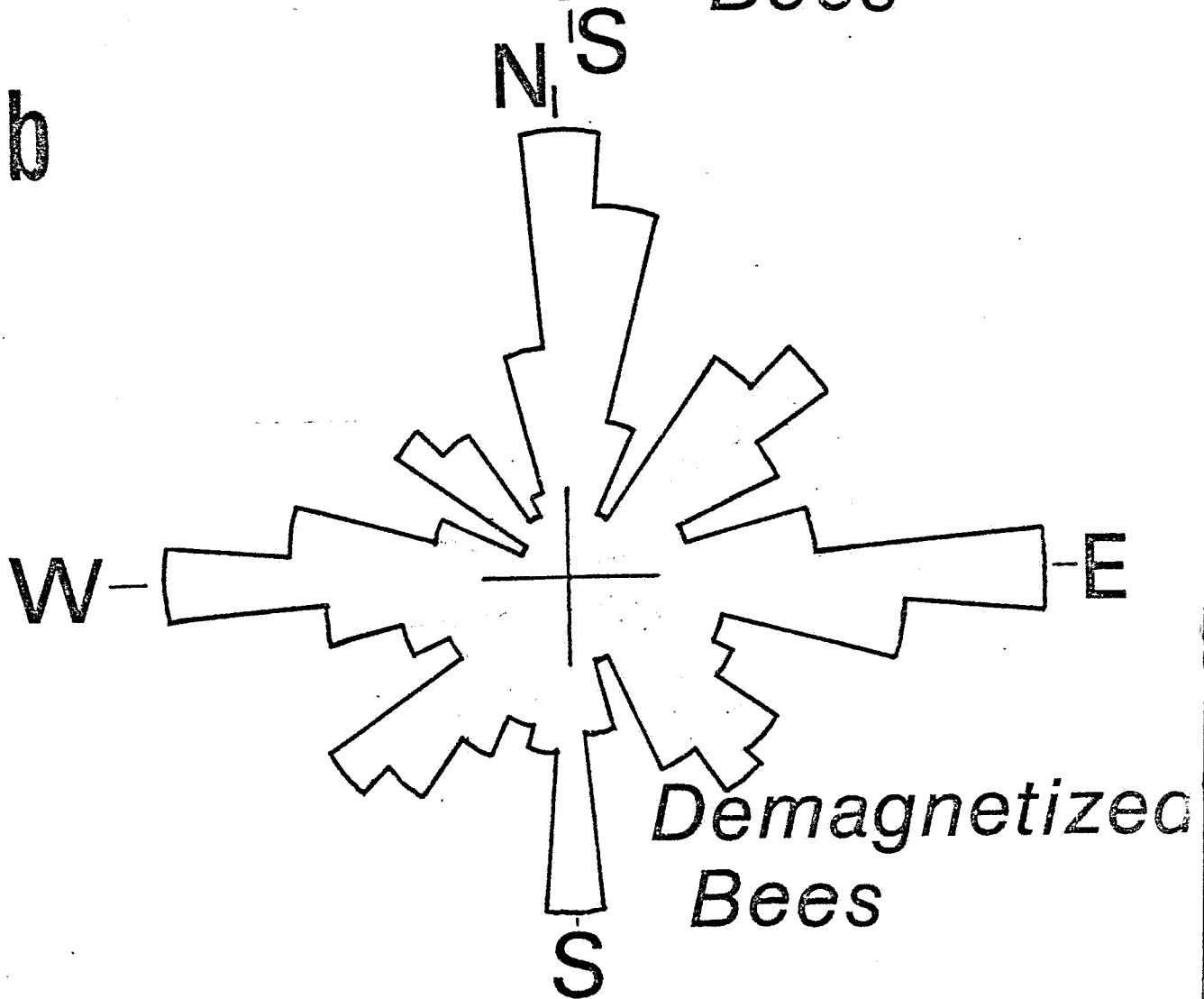
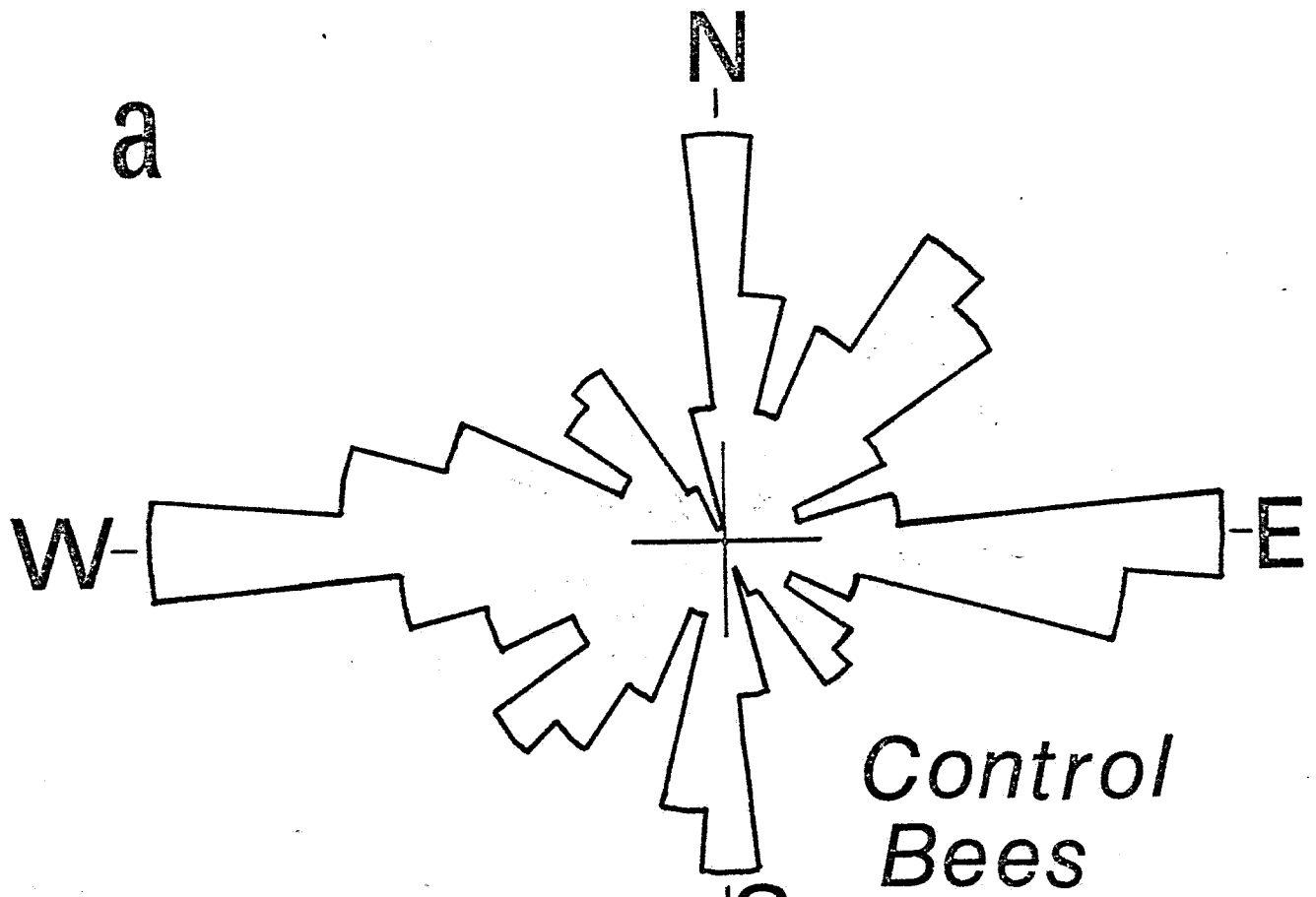
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5. The coil was fabricated by the coil shop of the Princeton University Plasma Physics Laboratory. It consisted of 2956 turns of #12 wire on an 11.5 cm air core, with water cooling between the inner and outer 18 layers. The resistance of the coil was 10.62 Ohms, while its inductance was 1.168H. We tuned the coil to near 60Hz by adding 5.8 μ F of capacitance in series. We ran the coil at 10.5-11.0 A from a Variac.
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FIGURE CAPTION

Figure 1. Directions of individual dance cycles for 12 bees under red light on a horizontal surface in an undisturbed earth's magnetic field. Magnetic directions are indicated. Each arm of the crosses in the center of the figures represents 5 dances.

- a) Before treatment, the dances are oriented to the eight points of the magnetic compass (n=438).
- b) After demagnetization with a 2100 Oe. AF coil in a null field, dance orientations continue to be oriented to the eight compass points (n=395).



SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED:

SEARCH, LINEAR, PLANAR, SQUARE, EIGEN, DIRECT, AND CROS

METHOD

AFTER THE DEMAGNETIZATION DATA IS ORDERED AND THE TABLES OF
 REMANENCE AND SUBTRACTED VECTORS FOR A SAMPLE PRINTED
 OUT, SUBROUTINE SEARCH IS CALLED AND, USING LINEAR,

SORT 053

SORT 054

SORT 055

SORT 056

SORT 057

SORT 058

SORT 059

SORT 060

LOCATES STRAIGHT SEGMENTS ALONG THE DEMAGNETIZATION PATH IN 3-SPACE. THESE POINTS ARE THEN USED TO GENERATE A MATRIX

SORT 061

OF SUMS OF SQUARES AND PRODUCTS FOR THE PRINCIPAL

SORT 062

COMPONENT ANALYSIS. DEMAGNETIZATION LINES AND PLANES

SORT 063

ARE ANCHORED TO THE ORIGIN IF IT IS INCLUDED, AND IF ONE

SORT 064

COMPONENT DOMINATES AN ANCHORED DEMAG PLANE, THE

SORT 065

CORRESPONDING REMAGNETIZATION CIRCLE WILL BE FOUND.

SORT 066

FINALLY, HOFFMAN-DAY DIRECTIONS ARE COMPUTED.

SORT 067

SORT 068

SORT 069

SORT 070

SORT 071

SORT 072

SORT 073

SORT 074

SORT 075

SORT 076

SORT 077

SORT 078

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SORT 091

SORT 092

SORT 093

SORT 094

SORT 095

SORT 096

SORT 097

SORT 098

SORT 099

SORT 100

SORT 101

SORT 102

DIMENSION X(20,99),Y(20,99),Z(20,99),DEMAG(20,99),SAMP1(99)

*,SAMP2(99),N(99),STRAT(99),X2(20),Y2(20),Z2(20),DMG2(20),SRCH(3),

* XG(20,99),YG(20,99),ZG(20,99),X2G(20),Y2G(20),Z2G(20)

DOUBLE PRECISION A,DMG,SAMP1,DEMAG,DMG2

DATA RA/0.017453/

LPT=LINE PRINTER,IN=CARD READER, ICARD=CARD PUNCH UNITS.

DATA LPT/6/,IN/5/,ICARD/7/

THE FIRST CARD GIVES THE SEARCH PARAMETERS.

READ(IN,5,ERR=7) SRCH

FORMAT(3F10.0)

IF(SRCH(1)) 7,7,410

SRCH(1) = 10.

SRCH(2) = 10.

CONTINUE

NS=1

ZERO ALL OF THE ARRAYS

DO 10 I=1,99

SAMP1(I)=0.0

SAMP2(I)=0.0

N(I)=0.0

STRAT(I)=0.0

DO 10 J=1,20

X(J,I)=0.0

Y(J,I)=0.0

Z(J,I)=0.0

XG(J,I) = 0.0

YG(J,I) = 0.0

ZG(J,I) = 0.0

DEMAG(J,I)=0.0

C		SORT 103
C	READ IN A DATA CARD, AND GENERATE THE VECTOR COMPONENTS.	SORT 104
C		SORT 105
15	READ(IN,20,END=400) A,B,CUM,GDEC,GINC,DEC,FINC,FINT,DMG	SORT 106
20	FORMAT(A5,F8.1,F10.1, 4F6.0 ,13X,E9.0,5X,A6)	SORT 107
	IF((B.EQ.0.).AND.(CUM.EQ.0.)) GO TO 200	SORT 108
	X1=FINT*COS(RA*FINC)*COS(RA*DEC)	SORT 109
	Y1=FINT*COS(RA*FINC)*SIN(RA*DEC)	SORT 110
	Z1= FINT*SIN(RA*FINC)	SORT 111
	X1G = FINT*COS(RA*GINC)*COS(RA*GDEC)	SORT 112
	Y1G = FINT*COS(RA*GINC)*SIN(RA*GDEC)	SORT 113
	Z1G = FINT*SIN(RA*GINC)	SORT 114
C		SORT 115
C	SORT THE DATA INTO THE PROPER SAMPLE	SORT 116
C		SORT 117
	DO 25 I=1,NS	SORT 118
	IF((A.EQ.SAMP1(I)).AND.(B.EQ.SAMP2(I))) GO TO 30	SORT 119
25	CONTINUE	SORT 120
C		SORT 121
C	CONTROL ONLY GETS HERE AT THE INITIATION OF A NEW SAMPLE	SORT 122
C		SORT 123
	SAMP1(NS)=A	SORT 124
	SAMP2(NS)=B	SORT 125
	STRAT(NS)=CUM	SORT 126
	N(NS)=1	SORT 127
	X(1,NS)=X1	SORT 128
	Y(1,NS)=Y1	SORT 129
	Z(1,NS)=Z1	SORT 130
	XG(1,NS) = X1G	SORT 131
	YG(1,NS) = Y1G	SORT 132
	ZG(1,NS) = Z1G	SORT 133
	DEMAG(1,NS)=DMG	SORT 134
	NS=NS+1	SORT 135
	GO TO 15	SORT 136
30	CONTINUE	SORT 137
C		SORT 138
C	I, THE INDEX FROM THE LAST DO LOOP, IS NOW THE SAMPLE # TO	SORT 139
C	WHICH THIS NEXT DEMAG STEP BELONGS	SORT 140
C		SORT 141
	N(I)=N(I)+1	SORT 142
	X(N(I),I)=X1	SORT 143
	Y(N(I),I)=Y1	SORT 144
	Z(N(I),I)=Z1	SORT 145
	XG(N(I),I) = X1G	SORT 146
	YG(N(I),I) = Y1G	SORT 147
	ZG(N(I),I) = Z1G	SORT 148
	DEMAG(N(I),I)=DMG	SORT 149
	GO TO 15	SORT 150
C		SORT 151
C	ALL DATA HAS NOW BEEN READ IN AND SORTED	SORT 152
200	NS=NS-1	SORT 153
		SORT 154

C	J DETERMINES WHICH SAMPLE IS TO BE PROCESSED NEXT	155
C		156
C	DO 300 J=1,NS	157
C		158
C	LIST THE REMNANCE VECTORS	159
C		160
210	WRITE(LPT,210) SAMP1(J),SAMP2(J)	161
	FORMAT('1 SAMPLE ',A5,1X,F5.1,' PROGRESSIVE DEMAG')	162
310	WRITE(LPT,310)	163
	FORMAT('0 MEASURED REMANENCE VECTORS: ')	164
315	WRITE(LPT,315)	165
	FORMAT(' DEMAG GDEC GINC SDEC SINC INTENSITY	166
	* /J0 ')	167
	F1=1.0	168
	NU=N(J)	169
	DO 330 I=1,NU	170
	X1=X(I,J)	171
	Y1=Y(I,J)	172
	Z1=Z(I,J)	173
	X1G = XG(I,J)	174
	Y1G = YG(I,J)	175
	Z1G = ZG(I,J)	176
C		177
C	POLAR CONVERTS THE CARTESIAN COORDINATES BACK INTO POLAR COORDS.	178
C		179
	CALL POLAR(X1,Y1,Z1,DEC,FINC,FINT)	180
	CALL POLAR(X1G, Y1G, Z1G, GDEC, GINC, FINT)	181
	IF(I.EQ.1) F1=FINT	182
	RAT=FINT/F1	183
330	WRITE(LPT,320) DEMAG(I,J),GDEC,GINC,DEC,FINC,FINT,RAT	184
320	FORMAT(' ',A6,4(3X,F5.1),3X,E9.3,4X,F6.3)	185
		186
C		187
C	GENERATE AND LIST THE SUBTRACTED VECTORS	188
C		189
	WRITE(LPT,215)	190
215	FORMAT('0 SUBTRACTED VECTORS:')	191
	WRITE(LPT,220)	192
220	FORMAT('0 DEMAG STEPS GDEC GINC SDEC SINC INTESORT	193
	* N. RATIO ')	194
	IF(N(J).LT.2) GO TO 300	195
	NJ=N(J)-1	196
	DO 230 I=1,NJ	197
	X1=X(I,J)-X(I+1,J)	198
	Y1=Y(I,J)-Y(I+1,J)	199
	Z1=Z(I,J)-Z(I+1,J)	200
	X1G = XG(I,J) - XG(I+1,J)	201
	Y1G = YG(I,J) - YG(I+1,J)	202
	Z1G = ZG(I,J) - ZG(I+1,J)	203
	CALL POLAR(X1,Y1,Z1,DEC,FINC,FINT)	204
	CALL POLAR(X1G, Y1G, Z1G, GDEC, GINC, FINT)	205
	IF(I.EQ.1) FININT=FINT	206
	IF(FININT.EQ.0.0) FININT=1.0	207
	RAT=FINT/FININT	208
225	WRITE(LPT,225) DEMAG(I,J),DEMAG(I+1,J),GDEC,GINC,DEC,FINC,FINT,RAT	209
230	FORMAT(' ',A6,' TO ',A6,5X, 4(F5.1,3X) ,1X,E9.3,5X,F7.3)	210
	CONTINUE	211

SUBROUTINE SEARCH

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PURPOSE

LOCATE LINEAR AND PLANAR SETS OF DEMAGNETIZATION POINTS
ALONG A DEMAGNETIZATION PATH, AND PERFORM LEAST-SQUARES
FITS TO THEM.

USAGE

CALL SEARCH(X,Y,Z,XG,YG,ZG,N,DEMAG,A,B,CUM,SRCH)

DESCRIPTION OF PARAMETERS

X - ARRAY OF X COMPONENTS IN DEMAG ORDER, TILT CORRECTED
Y - ARRAY OF Y COMPONENTS IN DEMAG ORDER, TILT CORRECTED
Z - ARRAY OF Z COMPONENTS IN DEMAG ORDER, TILT CORRECTED
XG- ARRAY OF X GEOGRAPHIC COORDINATES
YG- ARRAY OF Y GEOGRAPHIC COORDINATES
ZG- ARRAY OF Z GEOGRAPHIC COORDINATES
N - NUMBER OF STEPS IN THE DEMAGNETIZATION SEQUENCE
DEMAG - ARRAY CONTAINING THE ALPHANUMERIC STRING OF DEMAG
STEPS
A - FIRST PART OF SAMPLE NAME
B - SECOND (REAL) PART OF SAMPLE NAME
CUM - REAL VALUE OF STRATIGRAPHIC POSITION FROM BASE OF
FORMATION
SRCH - ARRAY OF SEARCH PARAMETERS. (1) - LINEARITY SONST,
(2) AND (3) ARE THE PLANARITY VALUES. (4) IS RETURNED
FROM THE LINE AND PLANE SUBROUTINES.

SUBROUTINES AND FUNCTIONS SUBPROGRAMS REQUIRED

LINEAR, PLANAR, POLAR, EIGEN, CROS, DIRECT

METHOD

THE LAST THREE POINTS IN THE DEMAGNETIZATION PATH ARE
TESTED FOR LINEARITY (VIA LINEAR). IF THEY PASS, THE NEXT
POINT IS INCLUDED AND AGAIN TESTED. IF THE FIRST THREE
FAIL, THE THREE POINTS ARE SHIFTED FURTHER ALONG THE DEMAG
PATH AND THE PROCEDURE IS REPEATED. ONCE A LINEAR SEGMENT
HAS BEEN LOCATED, IT IS EXPANDED AS MUCH AS POSSIBLE IN
BOTH DIRECTIONS UNTIL LINEARITY IS DESTROYED. WHEN THE
BOUNDING POINTS HAVE BEEN FOUND, THE LEAST SQUARE MATRIX IS
FORMED AND THE BEST DIRECTION IS EXTRACTED BY THE SSP
SUBROUTINE EIGEN. MANY LINEAR STRETCHES MAY BE FOUND
FROM ONE SPECIMEN. PLANES ARE SEARCHED FOR IN A SIMILAR
MANNER BUT USING A FOUR-POINT WINDOW.
THE ORIGIN IS ALWAYS INCLUDED AS THE N+1 DEMAG STEP

SRCH 001
SRCH 002
SRCH 003
SRCH 004
SRCH 005
SRCH 006
SRCH 007
SRCH 008
SRCH 009
SRCH 010
SRCH 011
SRCH 012
SRCH 013
SRCH 014
SRCH 015
SRCH 016
SRCH 017
SRCH 018
SRCH 019
SRCH 020
SRCH 021
SRCH 022
SRCH 023
SRCH 024
SRCH 025
SRCH 026
SRCH 027
SRCH 028
SRCH 029
SRCH 030
SRCH 031
SRCH 032
SRCH 033
SRCH 034
SRCH 035
SRCH 036
SRCH 037
SRCH 038
SRCH 039
SRCH 040
SRCH 041
SRCH 042
SRCH 043
SRCH 044
SRCH 045
SRCH 046
SRCH 047

C		SRCH 055
	SUBROUTINE SEARCH(X,Y,Z,XG,YG,ZG,N,DEMAG,A,B,CUM,SRCH)	SRCH 056
	DIMENSION X(20),Y(20),Z(20),DEMAG(20),E(9),FA(9),SRCH(3),	SRCH 057
	* HPLANE(30),IJ(2,10),EX(3),XG(20),YG(20),ZG(20),GPLANE(30)	SRCH 058
	DOUBLE PRECISION DEMAG,A,XORIG	SRCH 059
	DATA LPT/6/,IN/5/,ICARD/7/,XORIG/' ORIG'/,RA/0.017453/	SRCH 060
C		SRCH 061
C	MAKE THE ORIGIN THE N+1 TH DATA POINT	SRCH 062
C		SRCH 063
	X(N+1)=0.0	SRCH 064
	Y(N+1)=0.0	SRCH 065
	Z(N+1)=0.0	SRCH 066
	XG(N+1) = 0.0	SRCH 067
	YG(N+1) = 0.0	SRCH 068
	ZG(N+1) = 0.0	SRCH 069
	DEMAG(N+1) = XORIG	SRCH 070
	WRITE(LPT,235) SRCH(1)	SRCH 071
235	FORMAT('0 DIRECTIONS WHICH PASS ',F5.1,' DEGREE LINEARITY TEST:')	SRCH 072
	WRITE(LPT,60)	SRCH 073
60	FORMAT('0 DEMAG STEPS GDEC GINC SDEC SINC INTENS	SRCH 074
	*ITY # PTS NORMALIZED EIGENVALUES LOEND HIEND	SRCH 075
	*ER. ANG.')	SRCH 076
C		SRCH 077
C	I AND J ARE THE INDICES WHICH DETERMINE WHICH SEGMENT IN THE	SRCH 078
C	DEMAGNETIZATION PATH WILL BE EXAMINED FOR LINEARITY.. WE	SRCH 079
C	START WITH J=THE ORIGIN AND I= N-1 AS THE FIRST 3 POINTS.	SRCH 080
C		SRCH 081
	I=N-1	SRCH 082
	J=N+1	SRCH 083
C		SRCH 084
C	LINEAR CHECKS IF THE SEGMENT BETWEEN I AND J IS LINEAR	SRCH 085
C		SRCH 086
10	CALL LINEAR(X,Y,Z,I,J,TEST,SRCH)	SRCH 087
	IF(TEST.GT.0.) ERANG = SRCH(3)	SRCH 088
	IF(TEST) 15,15,20	SRCH 089
15	I=I-1	SRCH 090
	J=J-1	SRCH 091
	IF(I.LT.1) GO TO 100	SRCH 092
	GO TO 10	SRCH 093
20	IF(I.LE.1) GO TO 30	SRCH 094
	I=I-1	SRCH 095
	CALL LINEAR(X,Y,Z,I,J,TEST,SRCH)	SRCH 096
	IF(TEST.GT.0.) ERANG = SRCH(3)	SRCH 097
	IF(TEST) 25,25,20	SRCH 098
25	I=I+1	SRCH 099
30	IF(J.GE.N+1) GO TO 36	SRCH 100
	J=J+1	SRCH 101
	CALL LINEAR(X,Y,Z,I,J,TEST,SRCH)	SRCH 102
	IF(TEST.GT.0.) ERANG = SRCH(3)	SRCH 103
	IF(TEST) 35,35,30	SRCH 104
35	J=J-1	SRCH 105
36	CONTINUE	SRCH 106

C	NOW TRY JUMPING DOWN ONE POINT - IS THIS REALLY THE END?	SRCH 10
	IF(I.LT.3) GO TO 40	SRCH 108
	I = I-2	SRCH 109
	CALL LINEAR(X,Y,Z,I,J,TEST,SRCH)	SRCH 110
	IF(TEST.GT.0.) ERANG = SRCH(3)	SRCH 111
	IF(TEST) 37,37,38	SRCH 112
C	NOPE	SRCH 113
37	I = I+2	SRCH 114
	GO TO 40	SRCH 115
C	YEP	SRCH 116
38	I = I + 1	SRCH 117
	GO TO 20	SRCH 118
40	CONTINUE	SRCH 119
C		SRCH 120
C	WE HAVE FOUND A LINEAR SEGMENT AND LOCATED THE BOUNDARIES.	SRCH 121
C	TO PLEASE D.R. VAN ALSTINE, WE TEST FOR IMPROVEMENTS IN LINEAR-	SRCH 122
C	ITY BY ALTERNATELY THROWING OUT THE END POINTS OF THE LINE.	SRCH 123
C	THIS IS TO REMOVE ANY POSSIBLE BIAS FROM END OF LINE CURVES.	SRCH 124
	IPLG = 0	SRCH 125
	JPLG = 0	SRCH 126
	IF((J-I+1).LE.3) GO TO 46	SRCH 127
C	CHECK THE LOW DEMAG END FIRST	SRCH 128
	CALL LINEAR(X,Y,Z,I,J,TEST,SRCH)	SRCH 129
	TSTO = SRCH(3)	SRCH 130
	I = I+1	SRCH 131
	CALL LINEAR(X,Y,Z,I,J,TEST,SRCH)	SRCH 132
	TSTI = SRCH(3)	SRCH 133
	IF(TSTO-TSTI-1.) 41,41,42	SRCH 134
C	NO IMPROVEMENT	SRCH 135
41	I = I-1	SRCH 136
	GO TO 43	SRCH 137
C	IMPROVED LINEARITY	SRCH 138
42	IPLG = 1	SRCH 139
	ERANG = TSTI	SRCH 140
43	IF((J-I+1).LE.3) GO TO 46	SRCH 141
C	CHECK THE OTHER END	SRCH 142
C	DON'T THROW AWAY THE ORIGIN	SRCH 143
	IF(J.EQ.(N+1)) GO TO 46	SRCH 144
	J = J-1	SRCH 145
	CALL LINEAR(X,Y,Z,I,J,TEST,SRCH)	SRCH 146
	TSTJ = SRCH(3)	SRCH 147
	IF(TSTO-TSTJ-1.) 44,44,45	SRCH 148
C	NO IMPROVEMENT	SRCH 149
44	J = J+1	SRCH 150
	GO TO 46	SRCH 151
C	DID IMPROVE	SRCH 152
45	JPLG = 1	SRCH 153
	ERANG = TSTJ	SRCH 154

C	NOW WE SET UP THE MATRIX OF RESIDUAL SQUARES FOR THE LEAST SQUARE	SRCH 155
C	FITTING	SRCH 156
C	ANCHOR THE LINE IF IT INCLUDES THE ORIGIN	SRCH 157
46	FA(1) = 0.	SRCH 158
	IF(J.EQ.(N+1)) FA(1) = 1.E+6	SRCH 159
	CALL SQUARE(X,Y,Z,I,J,FA)	SRCH 160
C		SRCH 161
C	FA IS NOW THE MATRIX OF RESIDUAL SQUARES. ITS EIGEN VECTORS ARE	SRCH 162
C	ALIGNED ALONG THE PRINCIPAL AXES OF THE BEST FIT TO THE LINES	SRCH 163
C	CONTAINING THE POINTS IN 3-SPACE.	SRCH 164
C		SRCH 165
C	EIGEN EXTRACTS THE EIGENVECTORS.	SRCH 166
		SRCH 167
	CALL EIGEN(FA,E,3,0)	SRCH 168
	X1 = E(1)	SRCH 169
	Y1 = E(2)	SRCH 170
	Z1 = E(3)	SRCH 171
	SL = FA(1) + FA(3) + FA(6)	SRCH 172
	SL1 = FA(1)/SL	SRCH 173
	SL2 = FA(3)/SL	SRCH 174
	SL3 = FA(6)/SL	SRCH 175
C	NOW FIND THE GEOGRAPHIC DIRECTIONS	SRCH 176
	FA(1) = 0.	SRCH 177
	IF(J.EQ.(N+1)) FA(1) = 1.E+6	SRCH 178
	CALL SQUARE(XG,YG,ZG,I,J,FA)	SRCH 179
	CALL EIGEN(FA,E,3,0)	SRCH 180
	X1G = E(1)	SRCH 181
	Y1G = E(2)	SRCH 182
	Z1G = E(3)	SRCH 183
C		SRCH 184
C	THE RESULTING EIGENVECTOR MUST BE CHOSEN IN THE SAME DIRECTION	SRCH 185
C	AS THE REMANENCE. WE CHECK BY LOOKING AT THE DOT PRODUCT	SRCH 186
C		SRCH 187
	DOT=X1*(X(I)-X(J))+Y1*(Y(I)-Y(J))+Z1*(Z(I)-Z(J))	SRCH 188
	GDOT = X1G*(XG(I)-XG(J)) + Y1G*(YG(I)-YG(J)) + Z1G*(ZG(I)-ZG(J))	SRCH 189
C		SRCH 190
C	A NEGATIVE DOT VALUE MEANS THE VECTORS ARE ANTIPARALLEL	SRCH 191
C		SRCH 192
	IF(DOT) 50,50,55	SRCH 193
50	X1=-X1	SRCH 194
	Y1=-Y1	SRCH 195
	Z1=-Z1	SRCH 196
55	CALL POLAR(X1,Y1,Z1,DEC,FINC,FINT)	SRCH 197
	IF(GDOT) 57,57,61	SRCH 198
57	X1G = -X1G	SRCH 199
	Y1G = -Y1G	SRCH 200
	Z1G = -Z1G	SRCH 201
	CALL POLAR(X1G,Y1G,Z1G,GDEC,GINC,FINT)	SRCH 202

C		SRCH 203
C	THE INTENSITY OF THE LEAST-SQUARES DIRECTION IS ARBITRARILY	SRCH 204
C	TAKEN AS THE INTENSITY BETWEEN THE BOUNDING POINTS ON THE LINEAR	SRCH 205
C	SEGMENT.	SRCH 206
C		SRCH 207
	FINT=SQRT((X(I)-X(J))**2+(Y(I)-Y(J))**2+(Z(I)-Z(J))**2)	SRCH 208
C		SRCH 209
C	WRITE THE STABLE DIRECTION OUT TO THE LINE PRINTER	SRCH 210
C		SRCH 211
	JI = J-I+1	SRCH 212
	WRITE(LPT,65) DEMAG(I),DEMAG(J),GDEC,GINC,DEC,FINC,FINT,JI,SL1,	SRCH 213
	* SL2,SL3,IFLG,JFLG,ERANG	SRCH 214
65	FORMAT(A6,' TO ',A6,5X,4(F5.1,3X),1X,E9.3,1X,I4,5X,3F10.5,5X,	SRCH 215
	* 2I6,F10.1)	SRCH 216
C		SRCH 217
C	PUNCH OUT A CARD WHICH CAN BE USED IN OTHER PROGRAMS	SRCH 218
C		SRCH 219
	WRITE(ICARD,70) A,B,CUM,GDEC,GINC,DEC,FINC,ERANG,DEMAG(I),DEMAG(J)	SRCH 220
	*,JI	SRCH 221
70	FORMAT(A5,F5.1,3X,F10.1,4F6.1,' LINE ',3X,F6.1,3X,A5,1X,A5,1X,I2)	SRCH 222
C		SRCH 223
C	GO BACK AND LOOK FOR MORE LINEAR STRETCHES	SRCH 224
C		SRCH 225
	J=I+1 -IFLG	SRCH 226
	I=I-1 -IFLG	SRCH 227
	IF(I.LT.1) GO TO 100	SRCH 228
	GO TO 10	SRCH 229
100	WRITE(LPT,110)	SRCH 230
110	FORMAT('0 NO MORE LINEAR SEGMENTS')	SRCH 231
C		SRCH 232
C	NOW WE SEARCH THE SAME DATA SET FOR POINTS ON A PLANE	SRCH 233
	IF(N.LE.2) RETURN	SRCH 234
C		SRCH 235
	NPLANE = 0	SRCH 236
	WRITE(LPT,555) SRCH(2)	SRCH 237
555	FORMAT('0 NORMAL VECTORS TO LEAST-SQUARES DEMAGNETIZATION PLANES	SRCH 238
	*: ANGULAR STANDARD DEVIATIONS LESS THAN ',F5.1)	SRCH 239
	WRITE(LPT,560)	SRCH 240
560	FORMAT('0 DEMAG STEPS GDEC GINC SDEC SINC #PTS	SRCH 241
	* NORMALIZED EIGENVALUES # OF PLANES LOEND HIEND ER.	SRCH 242
	* ANG.')	SRCH 243
	I = N-2	SRCH 244
	J = N + 1	SRCH 245
C		SRCH 246
C	SUBROUTINE PLANE CHECKS IF THE POINTS BETWEEN I AND J LIE IN A PLANE	SRCH 247
C		SRCH 248
510	CALL PLANAR(X,Y,Z,I,J,TEST,SRCH)	SRCH 249
	IF(TEST.GT.0.) ERANG = SRCH(3)	SRCH 250
	IF(TEST) 515,515,520	SRCH 251
515	I = I-1	SRCH 252

	J = J-1	SRCH 253
	IF (I.LT.1) GO TO 600	SRCH 254
	GO TO 510	SRCH 255
520	IF (I.LE.1) GO TO 530	SRCH 256
	I = I-1	SRCH 257
	CALL PLANAR(X,Y,Z,I,J,TEST,SRCH)	SRCH 258
	IF (TEST.GT.0.) ERANG = SRCH(3)	SRCH 259
	IF (TEST) 525,525,520	SRCH 260
525	I = I + 1	SRCH 261
530	IF (J.GE.N+1) GO TO 536	SRCH 262
	J = J+1	SRCH 263
	CALL PLANAR(X,Y,Z,I,J,TEST,SRCH)	SRCH 264
	IF (TEST.GT.0.) ERANG = SRCH(3)	SRCH 265
	IF (TEST) 535,535,530	SRCH 266
535	J = J-1	SRCH 267
536	CONTINUE	SRCH 268
C	NOW TRY JUMPING DOWN ONE POINT AGAIN	SRCH 269
	IF (I.LT.3) GO TO 540	SRCH 270
	I = I-2	SRCH 271
	CALL PLANAR(X,Y,Z,I,J,TEST,SRCH)	SRCH 272
	IF (TEST.GT.0.) ERANG = SRCH(3)	SRCH 273
	IF (TEST) 537,537,538	SRCH 274
C	NOPE	SRCH 275
537	I = I+2	SRCH 276
	GO TO 540	SRCH 277
C	YEP	SRCH 278
538	I = I+1	SRCH 279
	GO TO 520	SRCH 280
540	CONTINUE	SRCH 281
	NPLANE = NPLANE + 1	SRCH 282
C		SRCH 283
C	WE HAVE FOUND A PLANE, AND EXPANDED THE BOUNDARIES.	SRCH 284
C	AGAIN, LOOK FOR IMPROVEMENTS BY THROWING AWAY THE ENDS.	SRCH 285
	IFLG = 0	SRCH 286
	JFLG = 0	SRCH 287
	IF ((J-I+1).LE.4) GO TO 546	SRCH 288
C	CHECK THE LOW END FIRST	SRCH 289
	CALL PLANAR(X,Y,Z,I,J,TEST,SRCH)	SRCH 290
	TSTO = SRCH(3)	SRCH 291
C	DON'T THROW AWAY THE NRM	SRCH 292
	IF (I.EQ.1) GO TO 543	SRCH 293
	I = I+1	SRCH 294
	CALL PLANAR(X,Y,Z,I,J,TEST,SRCH)	SRCH 295
	TSTI = SRCH(3)	SRCH 296
	IF (TSTO-TSTI-1.) 541,542,542	SRCH 297
C	NO IMPROVEMENT	SRCH 298
541	I = I-1	SRCH 299
	GO TO 543	SRCH 300
	PLANARITY IMPROVED	SRCH 301
542	IFLG = 1	SRCH 302
	ERANG = TSTI	SRCH 303
543	IF ((J-I+1).LE.4) GO TO 546	SRCH 304
C	CHECK THE OTHER SIDE	SRCH 305

C	DON'T THROW AWAY THE ORIGIN	SRCH 300
	IF(J.EQ.(N+1)) GO TO 546	SRCH 307
	J = J-1	SRCH 308
	CALL PLANAR(X,Y,Z,I,J,TEST,SRCH)	SRCH 309
	TSTJ = SRCH(3)	SRCH 310
	IF(TSTO-TSTJ -1.0) 544,545,545	SRCH 311
C	NO IMPROVEMENT	SRCH 312
544	J = J+1	SRCH 313
	GO TO 546	SRCH 314
C	IMPROVEMENT	SRCH 315
545	JFLG = 1	SRCH 316
	ERANG = TSTJ	SRCH 317
C	NOW WE FIND THE EIGENVECTOR NORMAL TO THE BEST-FITTING LEAST-	SRCH 318
C	SQUARES PLANE	SRCH 319
C		SRCH 320
546	FA(1) = 0.	SRCH 321
	IF(J.EQ.(N+1)) FA(1) = 1.E+6	SRCH 322
	CALL SQUARE(X,Y,Z,I,J,FA)	SRCH 323
	CALL EIGEN(FA,E,3,0)	SRCH 324
	SL = FA(1) + FA(3) + FA(6)	SRCH 325
	SL1 = FA(1)/SL	SRCH 326
	SL2 = FA(3)/SL	SRCH 327
	SL3 = FA(6)/SL	SRCH 328
C		SRCH 329
C	SL3 IS THE EIGENVALUE ASSOCIATED WITH THE NORMAL VECTOR TO THE	SRCH 330
C	PLANE, WHICH IS (E(7),E(8),E(9)).	SRCH 331
C		SRCH 332
	X1 = E(7)	SRCH 333
	Y1 = E(8)	SRCH 334
	Z1 = E(9)	SRCH 335
C	NOW DO IT FOR GEOGRAPHIC DIRECTIONS	SRCH 336
	FA(1) = 0.	SRCH 337
	IF(J.EQ.(N+1)) FA(1) = 1.E+6	SRCH 338
	CALL SQUARE(XG,YG,ZG,I,J,FA)	SRCH 339
	CALL EIGEN(FA,E,3,0)	SRCH 340
	X1G = E(7)	SRCH 341
	Y1G = E(8)	SRCH 342
	Z1G = E(9)	SRCH 343
C	THE EIGENVECTOR HAS ONE OF TWO POSSIBLE DIRECTIONS. FOR POLARITY	SRCH 344
C	INTERPRETATIONS, IT WOULD BE NICE TO HAVE A CONSISTENT	SRCH 345
C	REFERENCE. SUBROUTINE DIRECT DOES THIS.	SRCH 346
	CALL DIRECT(X,Y,Z,I,J,N,X1,Y1,Z1)	SRCH 347
550	CALL POLAR(X1,Y1,Z1,DEC,FINC,FINT)	SRCH 348
	CALL DIRECT(XG,YG,ZG,I,J,N,X1G,Y1G,Z1G)	SRCH 349
561	CALL POLAR(X1G,Y1G,Z1G,GDEC,GINC,FINT)	SRCH 350
C	STORE THE PLANE COMPONENTS FOR CALCULATING HOFFMAN-DAY DIRECTIONS.	SRCH 351
	IJ(1,NPLANE) = I	SRCH 352
	IJ(2,NPLANE) = J	SRCH 353
	HPLANE((NPLANE-1)*3+1) = X1	SRCH 354
	HPLANE((NPLANE-1)*3+2) = Y1	SRCH 355
	HPLANE((NPLANE-1)*3+3) = Z1	SRCH 356
	GPLANE((NPLANE-1)*3+1) = X1G	SRCH 357
	GPLANE((NPLANE-1)*3+2) = Y1G	SRCH 358
	GPLANE((NPLANE-1)*3+3) = Z1G	SRCH 359

C		SRCH 360
C	WRITE THE NORMAL PLANE TO THE LINE PRINTER	SRCH 361
C		SRCH 362
	JI = J-I+1	SRCH 363
	WRITE(LPT,565) DEMAG(I),DEMAG(J),GDEC,GINC,DEC,FINC,JI,SL1,SL2,	SRCH 364
	* SL3,NPLANE,IFLG,JFLG,ERANG	SRCH 365
565	FORMAT(A6,' TO ',A6,3X, 4(F5.1,3X) ,1X,I4,1X,3F10.5,5X,I6,6X,2I6,	SRCH 366
	* F10.1)	SRCH 367
C		SRCH 368
C	PUNCH OUT A CARD FOR THE BINGHAM STATISTICS	SRCH 369
C		SRCH 370
	WRITE(ICARD,570) A,B,CUM,GDEC,GINC,DEC,FINC,ERANG,DEMAG(I),	SRCH 371
	* DEMAG(J),JI	SRCH 372
570	FORMAT(A5,F5.1,3X,F10.1,4F6.1,' PLANE',3X,F6.1,3X,2(A5,1X),I2)	SRCH 373
C		SRCH 374
C	IF THIS WAS AN ANCHORED PLANE AND ONE OF THE COMPONENTS WAS MUCH	SRCH 375
C	LARGER THAN THE OTHER (NEARLY A LINE), COMPUTE THE DIRECTION OF	SRCH 376
C	A REMAGNETIZATION CIRCLE FOR IT.	SRCH 377
	IF(J.NE.(N+1)) GO TO 595	SRCH 378
	IF((ATAN(SQRT(SL2/SL1))/RA).GE.SRCH(1)) GO TO 595	SRCH 379
	FA(1) = -1.E+6	SRCH 380
	CALL SQUARE(X,Y,Z,I,J,FA)	SRCH 381
	CALL EIGEN(FA,E,3,0)	SRCH 382
	X1 = E(7)	SRCH 383
	Y1 = E(8)	SRCH 384
	Z1 = E(9)	SRCH 385
	FA(1) = -1.E+6	SRCH 386
	CALL SQUARE(XG,YG,ZG,I,J,FA)	SRCH 387
	CALL EIGEN(FA,E,3,0)	SRCH 388
	SL = FA(1) + FA(3) + FA(6)	SRCH 389
	SL1 = FA(1)/SL	SRCH 390
	SL2 = FA(3)/SL	SRCH 391
	SL3 = FA(6)/SL	SRCH 392
	ERANG = ATAN(SQRT(ABS(SL3/SL2+SL3/SL1)))/RA	SRCH 393
	X1G = E(7)	SRCH 394
	Y1G = E(8)	SRCH 395
	Z1G = E(9)	SRCH 396
	CALL DIRECT(X,Y,Z,I,J,N,X1,Y1,Z1)	SRCH 397
	CALL POLAR(X1,Y1,Z1,DEC,FINC,FINT)	SRCH 398
	CALL DIRECT(XG,YG,ZG,I,J,N,X1G,Y1G,Z1G)	SRCH 399
	CALL POLAR(X1G,Y1G,Z1G,GDEC,GINC,FINT)	SRCH 400
C	WRITE THIS TO THE LINE PRINTER	SRCH 401
	WRITE(LPT,575) GDEC,GINC,DEC,FINC,JI,SL1,SL2,SL3,ERANG	SRCH 402
575	FORMAT(5X,'CIRCLE',8X,4(F5.1,3X) ,1X,I4,1X,3F10.5,29X,F10.1)	SRCH 403
C	PUNCH A CARD	SRCH 404
	WRITE(ICARD,580) A,B,CUM,GDEC,GINC,DEC,FINC,ERANG,DEMAG(I),	SRCH 405
	* DEMAG(J),JI	SRCH 406
580	FORMAT(A5,F5.1,3X,F10.1,4F6.1,' CIRCLE',3X,F6.1,3X,2(A5,1X),I2)	SRCH 407
5	CONTINUE	SRCH 408

C		SRCH 409
C	GO BACK AND LOOK FOR MORE PLANES	SRCH 410
C		SRCH 411
	J = I + 2 - IFLG	SRCH 412
	I = I-1 -IFLG	SRCH 413
	IF(I.LT.1) GO TO 600	SRCH 414
	GO TO 510	SRCH 415
600	WRITE(LPT,610)	SRCH 416
610	FORMAT('0 NO MORE DEMAGNETIZATION PLANES')	SRCH 417
C	NOW LOOK FOR HOFFMAN-DAY DIRECTIONS	SRCH 418
	IF(NPLANE.LE.1) RETURN	SRCH 419
	WRITE(LPT,700)	SRCH 420
700	FORMAT('0 GENERALIZED HOFFMAN-DAY DIRECTIONS:')	SRCH 421
	WRITE(LPT,710)	SRCH 422
710	FORMAT('0 DEMAG STEPS GDEC GINC SDEC SINC')	SRCH 423
	NHOF = NPLANE-1	SRCH 424
	DO 780 K=1,NHOF	SRCH 425
C	THE DIRECTION WE WANT IS THAT OF THE CROSS PRODUCT OF TWO NORMAL	SRCH 426
C	VECTORS FROM NEIGHBORING PLANES. NOT ALL DIRECTIONS SO GENERATED	SRCH 427
C	ARE NECESSARILY HOFFMAN DAY TYPES, HOWEVER.	SRCH 428
	CALL CROS(EX,HPLANE(K*3+1),HPLANE((K-1)*3+1))	SRCH 429
	X1 = EX(1)	SRCH 430
	Y1 = EX(2)	SRCH 431
	Z1 = EX(3)	SRCH 432
	CALL CROS(EX,GPLANE(K*3+1),GPLANE((K-1)*3+1))	SRCH 433
	X1G = EX(1)	SRCH 434
	Y1G = EX(2)	SRCH 435
	Z1G = EX(3)	SRCH 436
C	AGAIN, WE MUST CHOSE THE PROPER DIRECTION FOR OUR INTERMEDIATE	SRCH 437
C	COMPONENT. THERE ARE THREE CASES TO CONSIDER:	SRCH 438
	I = IJ(1,K)	SRCH 439
	J = IJ(2,K+1)	SRCH 440
	IF(I.LE.J) GO TO 720	SRCH 441
	DOT = X1*(X(J)-X(I))+Y1*(Y(J)-Y(I))+Z1*(Z(J)-Z(I))	SRCH 442
	IF(DOT) 740,750,750	SRCH 443
720	IF(I.LT.J) GO TO 730	SRCH 444
C	I MUST = J. BACK OFF ONE POINT EACH WAY.	SRCH 445
	I = I+1	SRCH 446
	J = J-1	SRCH 447
	DOT = X1*(X(J)-X(I))+Y1*(Y(J)-Y(I))+Z1*(Z(J)-Z(I))	SRCH 448
	IF(DOT) 740,740,750	SRCH 449
C	I IS LESS THEN J. SWITCH THEM IN DOT	SRCH 450
730	DOT = X1*(X(I)-X(J))+Y1*(Y(I)-Y(J))+Z1*(Z(I)-Z(J))	SRCH 451
	IF(DOT) 740,750,750	SRCH 452
C	NEGATIVE DOT MEANS THEY ARE ANTIPARALLEL	SRCH 453
740	X1 = -X1	SRCH 454
	Y1 = -Y1	SRCH 455
	Z1 = -Z1	SRCH 456
750	CALL POLAR(X1,Y1,Z1,DEC,FINC,FINT)	SRCH 457

C	REPEAT THIS PROCEDURE FOR THE GEOGRAPHIC DIRECTIONS	SRCH 458
	I = IJ(1,K)	SRCH 459
	J = IJ(2,K+1)	SRCH 460
	IF(I.LE.J) GO TO 820	SRCH 461
	GDOT = X1G*(XG(J)-XG(I)) + Y1G*(YG(J)-YG(I)) + Z1G*(ZG(J)-ZG(I))	SRCH 462
	IF(GDOT) 840,850,850	SRCH 463
820	IF(I.LT.J) GO TO 830	SRCH 464
	I = I+1	SRCH 465
	J = J-1	SRCH 466
	GDOT = X1G*(XG(J)-XG(I)) + Y1G*(YG(J)-YG(I)) + Z1G*(ZG(J)-ZG(I))	SRCH 467
	IF(GDOT) 840,840,850	SRCH 468
830	GDOT = X1G*(XG(I)-XG(J)) + Y1G*(YG(I)-YG(J)) + Z1G*(ZG(I)-ZG(J))	SRCH 469
	IF(GDOT) 840,840,850	SRCH 470
840	X1G = -X1G	SRCH 471
	Y1G = -Y1G	SRCH 472
	Z1G = -Z1G	SRCH 473
850	CALL POLAR(X1G, Y1G, Z1G, GDEC, GINC, FINT)	SRCH 474
C	WRITE THIS TO THE PRINTER AND PUNCH A CARD.	SRCH 475
	WRITE(LPT,760) DEMAG(IJ(1,K+1)),DEMAG(IJ(2,K)),GDEC,GINC,DEC,FINC	SRCH 476
760	FORMAT(' ',A5,' TO ',A5,10X,4(F6.1,2X))	SRCH 477
	WRITE(ICARD,770) A,B,CUM,GDEC,GINC,DEC,FINC,DEMAG(IJ(1,K+1)),	SRCH 478
	* DEMAG(IJ(2,K))	SRCH 479
770	FORMAT(A5,F5.1,3X,F10.1,4F6.1,' HOFFMAN-DAY',4X,2(A5,1X))	SRCH 480
780	CONTINUE	SRCH 481
	RETURN	SRCH 482
	END	SRCH 483

C	SUBROUTINE LINEAR	LINE 001
C	J.L. KIRSCHVINK, MARCH, 1979	LINE 002
C		LINE 003
C	PURPOSE	LINE 004
C	TEST THE SEGMENT BETWEEN I AND J FOR LINEARITY	LINE 005
C		LINE 006
C	USAGE	LINE 007
C	CALL LINEAR(X,Y,Z,I,J,TEST,SRCH)	LINE 008
C		LINE 009
C	DESCRIPTION OF PARAMETERS	LINE 010
C	X - ARRAY OF REAL-VALUED X COORDINATE POINTS	LINE 011
C	Y - ARRAY OF REAL-VALUED Y COORDINATE POINTS	LINE 012
C	Z - ARRAY OF REAL-VALUED Z COORDINATE POINTS	LINE 013
C	I - LOWER BOUNDARY OF INTERVAL TO BE TESTED	LINE 014
C	J - UPPER BOUNDARY OF INTERVAL TO BE TESTED	LINE 015
C	TEST - RESULT OF TEST. IF TEST < 0., THE SEGMENT IS NOT	LINE 016
C	LINEAR. IF TEST IS >0, IT IS.	LINE 017
C	SRCH - THE ARRAY OF SEARCH PARAMETERS	LINE 018
C		LINE 019
C	REMARKS	LINE 020
C	THIS ROUTINE YIELDS A POSITIVE TEST IF THE ANGULAR	LINE 021
C	STANDARD DEVIATION IS LESS THAN SRCH(1), AND THE POINTS	LINE 022
C	ARE ROUGHLY IN ORDER.	LINE 023
C		LINE 024
C	SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED	LINE 025
C	EIGEN, SQUARE	LINE 026
C		LINE 027
C		LINE 028
C		LINE 029
C	SUBROUTINE LINEAR(X,Y,Z,I,J,TEST,SRCH)	LINE 030
C	DIMENSION X(20),Y(20),Z(20),T(9),E(9),SRCH(3)	LINE 031
C	DATA RA/0.017453/	LINE 032
C	CHECK THE EIGENVALUES FOR LINEARITY	LINE 033
C	T(1) = 0.	LINE 034
C	CALL SQUARE(X,Y,Z,I,J,T)	LINE 035
C	CALL EIGEN(T,E,3,1)	LINE 036
C	TEST=-1.0	LINE 037
C	FIND THE MAXIMUM ANGLE OF DEVIATION (M.A.D.)	LINE 038
C	T1 = ABS((T(3) + T(6))/T(1))	LINE 039
C	T1 = ATAN(SQRT(T1))/RA	LINE 040
C	SRCH(3) = T1	LINE 041
C	IF(T1.GT.SRCH(1)) RETURN	LINE 042
C	NOW SEE IF THE POINTS ARE ROUGHLY IN ORDER ALONG THE LINE	LINE 043
C	SEGLN=(X(I)-X(J))**2+(Y(I)-Y(J))**2 + (Z(I)-Z(J))**2	LINE 044
C	SEGLN=SQRT(SEGLN)	LINE 045
C	SUMLN=0.0	LINE 046
C	JI=J-1	LINE 047
C	DO 10 K=I,JI	LINE 048
10	SUMLN=SUMLN+SQRT((X(K)-X(K+1))**2+(Y(K)-Y(K+1))**2+(Z(K)-Z(K+1))	LINE 049
	***2)	LINE 050
	FLINE=SEGLN/SUMLN	LINE 051
C		LINE 052
C		LINE 053
	IF(FLINE.GR.0.90) TEST=1.0	LINE 054
	RETURN	LINE 055
	END	LINE 056

SUBROUTINE PLANAR

J.L. KIRSCHVINK, PRINCETON UNIVERSITY, MARCH 1979

PURPOSE

FIND SETS OF PLANAR POINTS ALONG DEMAGNETIZATION CURVES
IN 3-SPACE.

USAGE

CALL PLANAR (X,Y,Z,I,J,TEST,SRCH)

DESCRIPTION OF PARAMETERS

X - ARRAY OF X COMPONENTS IN DEMAG ORDER

Y - ARRAY OF Y COMPONENTS IN DEMAG ORDER

Z - ARRAY OF Z COMPONENTS IN DEMAG ORDER

I - LOWEST DEMAG STEP IN INTERVAL TO BE TESTED

J - HIGHEST DEMAG STEP IN INTERVAL TO BE TESTED

TEST -

A VALUE OF 1.0 IS GIVEN IF THE POINTS ARE ON A PLANE,

A NEGATIVE VALUE MEANS THEY FLUNK.

SRCH - SAME ARRAY AS IN SUBROUTINE LINEAR

SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED

EIGEN, SQUARE

METHOD

THE POINTS IN THE DEMAGNETIZATION WINDOW ARE FITTED TO
A LEAST-SQUARES PLANE VIA THE SAME ROUTINE USED IN THE
SEARCH PROGRAM. THE POINTS ARE PLANAR IF THE THIRD
EIGENVALUE IS MUCH LESS THAN THE OTHER TWO.

SUBROUTINE PLANAR (X,Y,Z,I,J,TEST,SRCH)

DIMENSION X(20),Y(20),Z(20),T(9),E(9),SRCH(3)

DATA RA/0.017453/

T(1) = 0.

CALL SQUARE(X,Y,Z,I,J,T)

CALL EIGEN(T,E,3,1)

FIND THE MAXIMUM ANGLE OF DEVIATION (M.A.D.)

T1 = ABS(T(6)/T(3) + T(6)/T(1))

T1 = ATAN(SQRT(T1))/RA

TEST = -1.

IF(T1.LE.SRCH(2)) TEST = 1.0

SRCH(3) = T1

RETURN

END

C	SUBROUTINE SQUARE	SQUIRE 01
C	J.L. KIRSCHVINK, PRINCETON UNIVERSITY, MARCH, 1979	SQUIRE 02
C		SQUIRE 03
C	PURPOSE	SQUIRE 04
C	CREATE THE MATRIX OF SQUARES AND PRODUCTS FOR THE	SQUIRE 05
C	POINTS ON THE SEGMENT OF THE DEMAGNETIZATION PATH	SQUIRE 06
C	BETWEEN I AND J	SQUIRE 07
C		SQUIRE 08
C	USEAGE	SQUIRE 09
C	CALL SQUARE(X,Y,Z,I,J,FA)	SQUIRE 10
C		SQUIRE 11
C	DESCRIPTION OF PARAMETERS	SQUIRE 12
C	X - ARRAY OF X COMPONENTS	SQUIRE 13
C	Y - ARRAY OF Y COMPONENTS	SQUIRE 14
C	Z - ARRAY OF Z COMPONENTS	SQUIRE 15
C	I - LOWEST DEMAG STEP (INTEGER)	SQUIRE 16
C	J - HIGHEST DEMAG STEP (INTEGER)	SQUIRE 17
C	FA - THE SIX ELEMENTS OF THE MATRIX ARE RETURNED IN	SQUIRE 18
C	THIS ARRAY, IN THE PROPER ORDER FOR EIGEN. ON INPUT,	SQUIRE 19
C	IF ABS(FA(1)) = 1.E+6, THE MATRIX IS ANCHORED TO THE	SQUIRE 20
C	ORIGIN. IF FA(1) = -1.E+6, INTENSITIES ARE TRUNCATED FOR	SQUIRE 21
C	REMAGNETIZATION CIRCLES AS WELL.	SQUIRE 22
C		SQUIRE 23
C	SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED	SQUIRE 24
C	NONE	SQUIRE 25
C		SQUIRE 26
C	METHOD	SQUIRE 27
C	THE POINTS IN THE ARRAYS X,Y, AND Z ARE TRANSLATED TO	SQUIRE 28
C	THE CENTROID, AND THEN THE MATRIX OF PRODUCTS AND	SQUIRE 29
C	SQUARES IS FORMED.	SQUIRE 30
C		SQUIRE 31
C	SUBROUTINE SQUARE(X,Y,Z,I,J,FA)	SQUIRE 32
C	DIMENSION X(20),Y(20),Z(20),X2(20),Y2(20),Z2(20),FA(9)	SQUIRE 33
C	FN = FLOAT(J-I+1)	SQUIRE 34
C	FIND THE COORDINATES OF THE CENTROID	SQUIRE 35
C	SUMX = 0.	SQUIRE 36
C	SUMY = 0.	SQUIRE 37
C	SUMZ = 0.	SQUIRE 38
C	IF (ABS(FA(1)).EQ. 1.E+6) GO TO 205	SQUIRE 39
C	DO 200 K = I,J	SQUIRE 40
C	SUMX = SUMX + X(K)/FN	SQUIRE 41
C	SUMY = SUMY + Y(K)/FN	SQUIRE 42
200	SUMZ = SUMZ + Z(K)/FN	SQUIRE 43
205	CONTINUE	SQUIRE 44

C	TRANSFORM THE CENTROID TO THE ORIGIN	SQUIRE 45
	DO 210 K = I,J	SQUIRE 46
	X2(K) = X(K) - SUMX	SQUIRE 47
	Y2(K) = Y(K) - SUMY	SQUIRE 48
210	Z2(K) = Z(K) - SUMZ	SQUIRE 49
C	NORMALIZE THE INTENSITY FOR THE REMAG CIRCLES	SQUIRE 50
	IF(FA(1).NE.-1.E+6) GO TO 220	SQUIRE 51
	DO 215 K = I,J	SQUIRE 52
	FINT = SQRT(X2(K)*X2(K) + Y2(K)*Y2(K) + Z2(K)*Z2(K))	SQUIRE 53
	IF(FINT.EQ.0.) GO TO 215	SQUIRE 54
	X2(K) = X2(K) / FINT	SQUIRE 55
	Y2(K) = Y2(K) / FINT	SQUIRE 56
	Z2(K) = Z2(K) / FINT	SQUIRE 57
215	CONTINUE	SQUIRE 58
220	CONTINUE	SQUIRE 59
C	GENERATE THE MOMENT OF INERTIA MATRIX	SQUIRE 60
	DO 230 K=1,6	SQUIRE 61
230	FA(K) = 0.	SQUIRE 62
	DO 240 K = I,J	SQUIRE 63
	FA(1) = FA(1) + X2(K)*X2(K)	SQUIRE 64
	FA(3) = FA(3) + Y2(K)*Y2(K)	SQUIRE 65
	FA(6) = FA(6) + Z2(K)*Z2(K)	SQUIRE 66
	FA(2) = FA(2) + X2(K)*Y2(K)	SQUIRE 67
	FA(4) = FA(4) + X2(K)*Z2(K)	SQUIRE 68
240	FA(5) = FA(5) + Y2(K)*Z2(K)	SQUIRE 69
	RETURN	SQUIRE 70
	END	SQUIRE 71

C	SUBROUTINE POLAR	POLR 001
C		POLR 002
C	PURPOSE	POLR 003
C	CONVERT X,Y,Z COMPONENTS BACK TO DEC,INC, AND INTENSITY	POLR 004
C		POLR 005
C	USEAGE	POLR 006
C	CALL POLAR(X,Y,Z,DEC,FINC,FINT)	POLR 007
C		POLR 008
C	DESCRIPTION OF PARAMETERS	POLR 009
C	X - REAL VALUE OF X COMPONENT	POLR 010
C	Y - REAL VALUE OF Y COMPONENT	POLR 011
C	Z - REAL VALUE OF Z COMPONENT	POLR 012
C	DEC - OUTPUT DECLINATION OF VECTOR	POLR 013
C	FINC - OUTPUT INCLINATION OF VECTOR	POLR 014
C	FINT - INTENSITY OF OUTPUT VECTOR	POLR 015
C		POLR 016
C	SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED	POLR 017
C	NONE	POLR 018
C		POLR 019
C		POLR 020
C		POLR 021
C	SUBROUTINE POLAR(XX,YY,ZZ,DEC,FINC,FINT)	POLR 022
C	POLAR CONVERTS CARTESIAN COORDINATES TO POLAR COORDINATES	POLR 023
	DATA DEG/57.29578/	POLR 024
	X = XX	POLR 025
	Y = YY	POLR 026
	Z = ZZ	POLR 027
	FINT=SQRT(X*X+Y*Y+Z*Z)	POLR 028
	IF(FINT.EQ.0.) DEC = 0.	POLR 029
	IF(FINT.EQ.0.) FINC = 0.	POLR 030
	IF(FINT.EQ.0.) GO TO 10	POLR 031
	X=X/FINT	POLR 032
	Y=Y/FINT	POLR 033
	Z=Z/FINT	POLR 034
	FINC= ARSIN(Z)*DEG	POLR 035
	IF((X.EQ.0.).AND.(Y.EQ.0.)) DEC = 0.	POLR 036
	IF((X.EQ.0.).AND.(Y.EQ.0.)) GO TO 10	POLR 037
	DEC=ATAN2(Y,X)*DEG	POLR 038
	IF(DEC) 5,10,10	POLR 039
5	DEC=360.0+DEC	POLR 040
10	CONTINUE	POLR 041
	RETURN	POLR 042
	END	POLR 043

C	SUBROUTINE DIRECT	DIRCT001
C	J.L. KIRSCHVINK, PRINCETON UNIVERSITY, MARCH 1979	DIRCT002
C		DIRCT003
C	PURPOSE	DIRCT004
C	FIND THE PROPER DIRECTION FOR A POLE TO A PLANE.	DIRCT005
	SUBROUTINE DIRECT(X,Y,Z,I,J,N,X1,Y1,Z1)	DIRCT006
	DIMENSION E(9), X(20), Y(20), Z(20)	DIRCT007
C	IF THE PLANE IS ANCHORED, THE PROBLEM IS SIMPLE	DIRCT008
	IF(J.NE.(N+1)) GO TO 20	DIRCT009
	E(4) = X(I)	DIRCT010
	E(5) = Y(I)	DIRCT011
	E(6) = Z(I)	DIRCT012
	E(7) = X(N)	DIRCT013
	E(8) = Y(N)	DIRCT014
	E(9) = Z(N)	DIRCT015
	CALL CROS(E(1),E(4),E(7))	DIRCT016
	DOT = E(1)*X1 + E(2)*Y1 + E(3)*Z1	DIRCT017
	IF(DOT) 30,30,40	DIRCT018
C		DIRCT019
C	NOT ANCHORED. USE A CRUDE CROSS PRODUCT.	DIRCT020
C		DIRCT021
20	CONTINUE	DIRCT022
C	FIND THE CENTROID	DIRCT023
	SUMX = 0.	DIRCT024
	SUMY = 0.	DIRCT025
	SUMZ = 0.	DIRCT026
	DO 25 K = I,J	DIRCT027
	SUMX = SUMX + X(K)	DIRCT028
	SUMY = SUMY + Y(K)	DIRCT029
25	SUMZ = SUMZ + Z(K)	DIRCT030
	FN = FLOAT(J-I+1)	DIRCT031
	SUMX = SUMX / FN	DIRCT032
	SUMY = SUMY / FN	DIRCT033
	SUMZ = SUMZ / FN	DIRCT034
	E(4) = SUMX - X(I)	DIRCT035
	E(5) = SUMY - Y(I)	DIRCT036
	E(6) = SUMZ - Z(I)	DIRCT037
	E(7) = X(J) - X(I)	DIRCT038
	E(8) = Y(J) - Y(I)	DIRCT039
	E(9) = Z(J) - Z(I)	DIRCT040
	CALL CROS(E(1),E(4),E(7))	DIRCT041
	DOT = E(1)*X1 + E(2)*Y1 + E(3)*Z1	DIRCT042
	IF(DOT) 30,30,40	DIRCT043
30	X1 = -X1	DIRCT044
	Y1 = -Y1	DIRCT045
	Z1 = -Z1	DIRCT046
40	CONTINUE	DIRCT047
	RETURN	DIRCT048
	END	DIRCT049

```

FUNCTION ARCOS (A)
  AA = 1. - A*A
  IF (AA) 1,1,2
1  ARCOS = 1.570796 - SIGN (1.570796,A)
  RETURN
2  ARCOS = ATAN2 (SQRT (AA) ,A)
  RETURN
END

```

```

ARCOS001
ARCOS002
ARCOS003
ARCOS004
ARCOS005
ARCOS006
ARCOS007
ARCOS008

```

```

FUNCTION ARSIN (A)
  AA = 1. - A*A
  IF (AA) 1,1,2
1  ARSIN = SIGN (1.570796,A)
  RETURN
2  ARSIN = ATAN (A/SQRT (AA))
  RETURN
END

```

```

ARSIN001
ARSIN002
ARSIN003
ARSIN004
ARSIN005
ARSIN006
ARSIN007
ARSIN008

```

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C  SUBROUTINE CROS ( C, A, B )
    CROSS PRODUCT      C = A X B.
    DIMENSION A(3), B(3), C(3)
    A1 = A(1)
    A2 = A(2)
    A3 = A(3)
    B1 = B(1)
    B2 = B(2)
    B3 = B(3)
    C(1) = A2*B3 - A3*B2
    C(2) = A3*B1 - A1*B3
    C(3) = A1*B2 - A2*B1
    RETURN
END

```

```

CROS 01
CROS 02
CROS 03
CROS 04
CROS 05
CROS 06
CROS 07
CROS 08
CROS 09
CROS 10
CROS 11
CROS 12
CROS 13
CROS 14

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C  SUBROUTINE UCROS ( U, A, B )
    UNIT CROSS PRODUCT.  ANSWER IS UNIT VECTOR PERP TO 'A' & 'B'.
    DIMENSION U(3), A(3), B(3)
    CALL CROS (U,A,B)
    CALL UNIT (U,U)
    RETURN
END

```

```

UCRS 001
UCRS 002
UCRS 003
UCRS 004
UCRS 005
UCRS 006
UCRS 007

```


SUBROUTINE UNIT (U, A)	UNIT 001
DIMENSION U(3), A(3)	UNIT 002
AA = SQRT(A(1)*A(1) + A(2)*A(2) + A(3)*A(3))	UNIT 003
IF (AA) 2, 2, 1	UNIT 004
1 AA = 1. / AA	UNIT 005
2 U(1) = AA * A(1)	UNIT 006
U(2) = AA * A(2)	UNIT 007
U(3) = AA * A(3)	UNIT 008
RETURN	UNIT 009
END	UNIT 010
FUNCTION DOT (A,B)	DOT 001
DIMENSION A(1), B(1)	DOT 002
DOT = A(1)*B(1) + A(2)*B(2) + A(3)*B(3)	DOT 003
RETURN	DOT 004
END	DOT 005
SUBROUTINE AZDIST (A, B, AZ, DIST)	AZDST001
C AZ IS THE AZIMUTH OF THE GREAT CIRCLE CONNECTING VECTOR A AND B WITH	AZDST002
C RESPECT TO A N-S MERIDIAN, AZ = ARCOS(DOT(B X A, FN X A))	AZDST003
C DIST IS THE DISTANCE BETWEEN A AND B , DIST = ARCOS(DOT(A, B)) * RADIUS	AZDST004
DIMENSION A(3), B(3), FN(3), AXFN(3), AXB(3)	AZDST005
FN(1) = 00.0	AZDST006
FN(2) = 00.0	AZDST007
FN(3) = 1.0	AZDST008
CALL UCROS (AXB, A, B)	AZDST009
CALL UCROS (AXFN, A, FN)	AZDST010
AZ = ARCOS(DOT(AXB, AXFN)) * 57.29578	AZDST011
C IF DOT>0, THEN AZ IS BETWEEN 0 AND 90 DEGREES, IF DOT .0, THEN AZ	AZDST012
C IS BETWEEN 90 AND 180 DEGREES	AZDST013
C IF DOT(B, AXFN) IS .0, THEN AZ IS BETWEEN 0 AND 180 DEGREES	AZDST014
C IF DOT(B, AXFN) IS >0 , THEN AZ IS BETWEEN 180 AND 360 DEGREES	AZDST015
IF(DOT(B, AXFN)) 2, 1, 1	AZDST016
1 AZ = 360 - AZ	AZDST017
2 CONTINUE	AZDST018
DIST = ARCOS(DOT(A, B))	AZDST019
IF(AZ.GT.180.) AZ = AZ - 180.	AZDST020
RETURN	AZDST021
END	AZDST022

C	MESH		MESH 001
C		J.L. KIRSCHVINK, PRINCETON UNIVERSITY, MARCH 1979	MESH 002
C		VERSION 1	MESH 003
C			MESH 004
C	PURPOSE		MESH 005
C		COMPUTE FISHERIAN AND BINGHAM STATISTICS ON BOTH LINE AND	MESH 006
C		PLANE DATA, AND USE BOTH SETS IN A COMBINED ESTIMATE OF THE	MESH 007
C		REMANENCE DIRECTION.	MESH 008
C			MESH 009
C			MESH 010
	DIMENSION	GDL(100), GIL(100), SDL(100), SIL(100), GDP(100),	MESH 011
	*	GIP(100), SDP(100), SIP(100), COMENT(19), GT(9), ST(9), GE(9),	MESH 012
	*	SE(9), GP(9), SP(9), GQ(9), SQ(9), TSDL(200), TSIL(200), TGDL(200),	MESH 013
	*	TGIL(200)	MESH 014
		DATA PLANE/'PLAN'/, CIRCLE/'CIRC'/, IN/5/, LPT/6/	MESH 015
C	5	5 SORT THINGS INTO LINE AND PLANE MEASUREMENTS	MESH 016
	10	10 READ(IN,10,END=200) ITYP, COMENT	MESH 017
		FORMAT(I1,19A4)	MESH 018
		WRITE(LPT,11) COMENT	MESH 019
	11	11 FORMAT('1', 19A4)	MESH 020
		IF(ITYP.EQ.1) WRITE(LPT,8)	MESH 021
	8	8 FORMAT(' ALL DATA IS TREATED AS LINES')	MESH 022
		NL = 0	MESH 023
		NP = 0	MESH 024
		FSDEC = 0.	MESH 025
		FSINC = 0.	MESH 026
		FGDEC = 0.	MESH 027
		FGINC = 0.	MESH 028
	15	15 READ(IN,20,END=50) SAMP, GDEC, GINC, SDEC, SINC, TYPE	MESH 029
	20	20 FORMAT(5X,F5.1,13X,4F6.1,2X,A4)	MESH 030
		IF(SAMP.EQ.0.) GO TO 50	MESH 031
		IF(ITYP.EQ.1) GO TO 25	MESH 032
		IF((TYPE.EQ.PLANE).OR.(TYPE.EQ.CIRCLE)) GO TO 30	MESH 033
	25	25 CONTINUE	MESH 034
C		THESE ARE LINES	MESH 035
		NL = NL + 1	MESH 036
		GDL(NL) = GDEC	MESH 037
		GIL(NL) = GINC	MESH 038
		SDL(NL) = SDEC	MESH 039
		SIL(NL) = SINC	MESH 040
		GO TO 15	MESH 041
C		THESE ARE POLES TO PLANES AND CIRCLES	MESH 042
	30	30 NP = NP + 1	MESH 043
		GDP(NP) = GDEC	MESH 044
		GIP(NP) = GINC	MESH 045
		SDP(NP) = SDEC	MESH 046
		SIP(NP) = SINC	MESH 047
		GO TO 15	MESH 048
	50	50 CONTINUE	MESH 049
C		PRINT OUT A LIST OF THE DATA	MESH 050
		WRITE(LPT,51)	MESH 051
	51	51 FORMAT('0 LINES: GDEC GINC SDEC SINC')	MESH 052
		IF(NL.LT.1) GO TO 57	MESH 053

	DO 52 K = 1,NL	MESH 054
52	WRITE(LPT,53) GDL(K),GIL(K),SDL(K),SIL(K)	MESH 055
53	FORMAT(9X,4F7.1)	MESH 056
57	CONTINUE	MESH 057
	WRITE(LPT,54)	MESH 058
54	FORMAT('0 PLANES: GDEC GINC SDEC SINC')	MESH 059
	IF(NP.LT.1) GO TO 61	MESH 060
	DO 56 K = 1,NP	MESH 061
56	WRITE(LPT,53) GDP(K),GIP(K),SDP(K),SIP(K)	MESH 062
61	CONTINUE	MESH 063
C		MESH 064
C	NOW ALL OF THE DATA ARE IN, COMPUTE FISHER STATISTICS ON THE	MESH 065
C	LINEAR DIRECTIONS, IF ANY	MESH 066
C		MESH 067
	IF(NL.LE.1) GO TO 80	MESH 068
	CALL FISHER(GDL,GIL,NL,GR,GK,GALPHA,GTHETA,FGDEC,FGINC)	MESH 069
	CALL FISHER(SDL,SIL,NL,SR,SK,SALPHA,STHETA,FSDEC,FSINC)	MESH 070
	WRITE(LPT,11) COMENT	MESH 071
	IF(ITYP.EQ.1) WRITE(LPT,8)	MESH 072
	WRITE(LPT,55) NL	MESH 073
55	FORMAT('0 FISHERIAN STATISTICS ON LINE DATA FROM ',I4,' SPECIMENS	MESH 074
	*, ')	MESH 075
	WRITE(LPT,60)	MESH 076
60	FORMAT('0',24X,' DEC INC R KAPPA C.S.	MESH 077
	*D. A95 ')	MESH 078
	WRITE(LPT,63) FGDEC,FGINC,GR,GK,GTHETA,GALPHA	MESH 079
63	FORMAT(' BEFORE TILT CORRECTION:',2F10.1,F10.4,3F10.1)	MESH 080
	WRITE(LPT,64) FSDEC,FSINC,SR,SK,STHETA,SALPHA	MESH 081
64	FORMAT(' AFTER TILT CORRECTION:',2F10.1,F10.4,3F10.1)	MESH 082
C		MESH 083
C	NOW CALCULATE BINGHAM STATISTICS ON THE SAME LINE DATA	MESH 084
C		MESH 085
C	WRITE THE BINGHAM HEADER	MESH 086
	WRITE(LPT,70)	MESH 087
70	FORMAT('0 BINGHAM STATISTICS:')	MESH 088
	WRITE(LPT,72)	MESH 089
72	FORMAT('0',20X,' N DEC INC K1 K2 OV.AZ. ST	MESH 090
	*.DEVIATION ANG5 BINGHM 95% ANG EIGENVALUES')	MESH 091
C	GENERATE THE MATRIX OF SUMS OF SQUARES AND PRODUCTS	MESH 092
	CALL SUMPRD(GDL,GIL,NL,GT)	MESH 093
	CALL SUMPRD(SDL,SIL,NL,ST)	MESH 094
	CALL EIGEN(GT,GE,3,0)	MESH 095
	CALL EIGEN(ST,SE,3,0)	MESH 096
	CALL POLAR(GE(1),GE(2),GE(3),GDEC,GINC,FINT)	MESH 097
	CALL POLAR(SE(1),SE(2),SE(3),SDEC,SINC,FINT)	MESH 098
C	MAKE THESE PARALLEL THE FISHER DIRECTION	MESH 099
	CALL FDOT(FGDEC,FGINC,GDEC,GINC)	MESH 100
	CALL FDOT(FSDEC,FSINC,SDEC,SINC)	MESH 101
	NOW FIND THE BINGHAM CONCENTRATION PARAMETERS	MESH 102
	CALL BINGHM(GT(1),GT(3),GT(6),GK1,GK2)	MESH 103
	CALL BINGHM(ST(1),ST(3),ST(6),SK1,SK2)	MESH 104

C	FIND THE ORIENTATION OF THE ERROR ELLIPSES FOR LINE DATA	MESH 105
	CALL AZDIST(GE(1),GE(4),GAZ,DIST)	MESH 106
	CALL AZDIST(SE(1),SE(4),SAZ,DIST)	MESH 107
C	FIND THE ONE-SIGMA AND BINGHAM 95% CONFIDENCE ANGLES ABOUT EACH	MESH 108
C	EIGENVECTOR	MESH 109
	CALL ANGLES(GK1,GK2,GT,GSD1,GSD2,GSD3,GA951,GA952,GA953)	MESH 110
	CALL ANGLES(SK1,SK2,ST,SSD1,SSD2,SSD3,SA951,SA952,SA953)	MESH 111
	WRITE(LPT,75) NL,GDEC,GINC,GK1,GK2,GAZ,GSD2,GSD3,GA952,GA953,	MESH 112
	* GT(1),GT(3),GT(6)	MESH 113
75	FORMAT('0 LINES PRE-TILT: ',I3,2F7.1,2F10.2,F7.1,3X,2F7.1,	MESH 114
	* 2X,2F7.1,2X,3F8.3)	MESH 115
	WRITE(LPT,76) NL,SDEC,SINC,SK1,SK2,SAZ,SSD2,SSD3,SA952,SA953,	MESH 116
	* ST(1),ST(3),ST(6)	MESH 117
76	FORMAT(' POST-TILT: ',I3,2F7.1,2F10.2,F7.1,3X,2F7.1,	MESH 118
	* 2X,2F7.1,2X,3F8.3)	MESH 119
80	CONTINUE	MESH 120
C		MESH 121
C	NOW USE BINGHAM AND WATSON STATISTICS ON THE POLES TO THE	MESH 122
C	PLANES AND CIRCLES	MESH 123
C		MESH 124
	IF(NP.LE.1) GO TO 100	MESH 125
	CALL SUMPRD(GDP,GIP,NP,GP)	MESH 126
	CALL SUMPRD(SDP,SIP,NP,SP)	MESH 127
	CALL EIGEN(GP,GQ,3,0)	MESH 128
	CALL EIGEN(SP,SQ,3,0)	MESH 129
	CALL POLAR(GQ(7),GQ(8),GQ(9),GDEC,GINC,FINT)	MESH 130
	CALL POLAR(SQ(7),SQ(8),SQ(9),SDEC,SINC,FINT)	MESH 131
	CALL FDOT(FGDEC,FGINC,GDEC,GINC)	MESH 132
	CALL FDOT(FSDEC,FSINC,SDEC,SINC)	MESH 133
	CALL BINGHM(GP(1),GP(3),GP(6),GK1,GK2)	MESH 134
	CALL BINGHM(SP(1),SP(3),SP(6),SK1,SK2)	MESH 135
	CALL AZDIST(GQ(7),GQ(4),GAZ,DIST)	MESH 136
	CALL AZDIST(SQ(7),SQ(4),SAZ,DIST)	MESH 137
	CALL ANGLES(GK1,GK2,GP,GSD1,GSD2,GSD3,GA951,GA952,GA953)	MESH 138
	CALL ANGLES(SK1,SK2,SP,SSD1,SSD2,SSD3,SA951,SA952,SA953)	MESH 139
	WRITE(LPT,83) NP,GDEC,GINC,GK1,GK2,GAZ,GSD2,GSD1,GA952,GA951,	MESH 140
	* GP(1),GP(3),GP(6)	MESH 141
83	FORMAT('0 PLANES PRE-TILT: ',I3,2F7.1,2F10.2,F7.1,3X,2F7.1,	MESH 142
	* 2X,2F7.1,2X,3F8.3)	MESH 143
	WRITE(LPT,76) NP,SDEC,SINC,SK1,SK2,SAZ,SSD2,SSD1,SA952,SA951,	MESH 144
	* SP(1),SP(3),SP(6)	MESH 145
	GPLMIN = GP(6)	MESH 146
	SPLMIN = SP(6)	MESH 147
90	CONTINUE	MESH 148
C		MESH 149
C	NOW FIND THE COMMON DIRECTION FOR METHOD 1 - SUBTRACT THE MATRICES	MESH 150
C		MESH 151
	CALL SUMPRD(GDP,GIP,NP,GP)	MESH 152
	CALL SUMPRD(SDP,SIP,NP,SP)	MESH 153
	CALL SUMPRD(GDL,GIL,NL,GT)	MESH 154
	CALL SUMPRD(SDL,SIL,NL,ST)	MESH 155
C	SUBTRACT THEM	MESH 156
	DO 92 K = 1,6	MESH 157
	GP(K) = GP(K) - GT(K)	MESH 158
92	SP(K) = SP(K) - ST(K)	MESH 159

	FIND THE EIGENVECTORS	MESH 160
	CALL EIGEN(GP, GQ, 3, 0)	MESH 161
	CALL EIGEN(SP, SQ, 3, 0)	MESH 162
	CALL POLAR(GQ(7), GQ(8), GQ(9), GDEC, GINC, FINT)	MESH 163
	CALL POLAR(SQ(7), SQ(8), SQ(9), SDEC, SINC, FINT)	MESH 164
	CALL FDOT(FGDEC, FGINC, GDEC, GINC)	MESH 165
	CALL FDOT(FSDEC, FSINC, SDEC, SINC)	MESH 166
	CALL AZDIST(GQ(7), GQ(4), GAZ, DIST)	MESH 167
	CALL AZDIST(SQ(7), SQ(4), SAZ, DIST)	MESH 168
C	THE REST OF THE PARAMETERS CANNOT YET BE CALCULATED	MESH 169
	NSUM = NL + NP	MESH 170
	WRITE(LPT, 95) NSUM, GDEC, GINC, GAZ, GP(1), GP(3), GP(6)	MESH 171
95	FORMAT('0 METHOD 1 PRE-TILT: ', I3, 2F7.1, 20X, F7.1, 35X, 3F8.3)	MESH 172
	WRITE(LPT, 96) NSUM, SDEC, SINC, SAZ, SP(1), SP(3), SP(6)	MESH 173
96	FORMAT(' POST-TILT: ', I3, 2F7.1, 20X, F7.1, 35X, 3F8.3)	MESH 174
C		MESH 175
100	CONTINUE	MESH 176
C		MESH 177
C	NOW DO METHOD 2 - FIRST, FIND TWO ORTHOGONAL POINTS ON THE	MESH 178
C	GIRDLE FOR EACH LINE DATA POINT, COMPUTE THE TOTAL MATRIX, AND	MESH 179
C	FIND THE CORRESPONDING DIRECTION AND STATISTICS.	MESH 180
C		MESH 181
C	GENERATE THE ORTHOGONAL DIRECTIONS	MESH 182
C		MESH 183
	DO 110 I = 1, NL	MESH 184
	K = 2*I - 1	MESH 185
C	FIRST FIND ANY POINT 90 DEGREES AWAY FROM THE LINE DIRECTIONS.	MESH 186
C		
C	DECLINATIONS REMAIN THE SAME	MESH 187
	TGDL(K) = GDL(I)	MESH 188
	TSDL(K) = SDL(I)	MESH 189
C	INCLINATION IS 90 DEGREES AWAY	MESH 190
	IF(GIL(I).LT.0.) TGIL(K) = 90. + GIL(I)	MESH 191
	IF(SIL(I).LT.0.) TSIL(K) = 90. + SIL(I)	MESH 192
	IF(GIL(I).GE.0.) TGIL(K) = GIL(I) - 90.	MESH 193
	IF(SIL(I).GE.0.) TSIL(K) = SIL(I) - 90.	MESH 194
C	THE POINT PERPENDICULAR TO THESE TWO IS 90 DEG. AWAY IN DEC,	MESH 195
C	WITH A 0 DEG. INCLINATION.	MESH 196
	TGDL(K+1) = GDL(I) + 90.	MESH 197
	TSDL(K+1) = SDL(I) + 90.	MESH 198
	IF(TGDL(K+1).GT.360.) TGDL(K+1) = 360. - TGDL(K+1)	MESH 199
	IF(TSDL(K+1).GT.360.) TSDL(K+1) = 360. - TSDL(K+1)	MESH 200
	TGIL(K+1) = 0.	MESH 201
110	TSIL(K+1) = 0.	MESH 202
C	NOW MAKE THE MATRIX OF SUMS OF SQUARES AND PRODUCTS	MESH 203
	NLT = 2*NL	MESH 204
	CALL SUMPRD(TGDL, TGIL, NLT, GT)	MESH 205
	CALL SUMPRD(TSDL, TSIL, NLT, ST)	MESH 206

C	REDUCE EACH TERM BY A FACTOR OF 2 TO GIVE HALF WEIGHT TO	MESH 207
C	EACH OF THE NEW POINTS	MESH 208
	DO 115 K = 1,6	MESH 209
	GT(K) = GT(K)/2.	MESH 210
115	ST(K) = ST(K)/2.	MESH 211
C	ADD THIS MATRIX TO THE POLE DATA FROM THE PLANES	MESH 212
	IF(NP.LE.1) GO TO 130	MESH 213
	CALL SUMPRD(GDP,GIP,NP,GP)	MESH 214
	CALL SUMPRD(SDP,SIP,NP,SP)	MESH 215
	DO 120 K = 1,6	MESH 216
	GP(K) = GP(K) + GT(K)	MESH 217
120	SP(K) = SP(K) + ST(K)	MESH 218
	CALL EIGEN(GP,GQ,3,0)	MESH 219
	CALL EIGEN(SP,SQ,3,0)	MESH 220
	CALL POLAR(GQ(7),GQ(8),GQ(9),GDEC,GINC,FINT)	MESH 221
	CALL POLAR(SQ(7),SQ(8),SQ(9),SDEC,SINC,FINT)	MESH 222
	CALL FDOT(FGDEC,FGINC,GDEC,GINC)	MESH 223
	CALL FDOT(FSDEC,FSINC,SDEC,SINC)	MESH 224
	CALL BINGHM(GP(1),GP(3),GP(6),GK1,GK2)	MESH 225
	CALL BINGHM(SP(1),SP(3),SP(6),SK1,SK2)	MESH 226
	CALL AZDIST(GQ(7),GQ(4),GAZ,DIST)	MESH 227
	CALL AZDIST(SQ(7),SQ(4),SAZ,DIST)	MESH 228
	CALL ANGLES(GK1,GK2,GP,GSD1,GSD2,GSD3,GA951,GA952,GA953)	MESH 229
	CALL ANGLES(SK1,SK2,SP,SSD1,SSD2,SSD3,SA951,SA952,SA953)	MESH 230
	WRITE(LPT,123) NSUM,GDEC,GINC,GK1,GK2,GAZ,GSD2,GSD1,GA952,GA951,	MESH 231
	* GP(1), GP(3), GP(6)	MESH 232
123	FORMAT('0 METHOD 2 PRE-TILT: ',I3,2F7.1,2F10.2,F7.1,3X,2F7.1,	MESH 233
	* 2X,2F7.1,2X,3F8.3)	MESH 234
	WRITE(LPT, 76) NSUM,SDEC,SINC,SK1,SK2,SAZ,SSD2,SSD1,SA952,SA951,	MESH 235
	* SP(1),SP(3),SP(6)	MESH 236
	GCLMIN = GP(6)	MESH 237
	SCLMIN = SP(6)	MESH 238
130	CONTINUE	MESH 239
	IF(NL.LE.1) GO TO 140	MESH 240
C		MESH 241
C	FINALLY, CALCULATE BINGHAM STATISTICS ON THE TRANSFORMED LINE DATA	MESH 242
C		MESH 243
	CALL EIGEN(GT,GQ,3,0)	MESH 244
	CALL EIGEN(ST,SQ,3,0)	MESH 245
	CALL POLAR(GQ(7),GQ(8),GQ(9),GDEC,GINC,FINT)	MESH 246
	CALL POLAR(SQ(7),SQ(8),SQ(9),SDEC,SINC,FINT)	MESH 247
	CALL FDOT(FGDEC,FGINC,GDEC,GINC)	MESH 248
	CALL FDOT(FSDEC,FSINC,SDEC,SINC)	MESH 249
	CALL BINGHM(GT(1),GT(3),GT(6),GK1,GK2)	MESH 250
	CALL BINGHM(ST(1),ST(3),ST(6),SK1,SK2)	MESH 251
	CALL AZDIST(GQ(7),GQ(4),GAZ,DIST)	MESH 252
	CALL AZDIST(SQ(7),SQ(4),SAZ,DIST)	MESH 253
	CALL ANGLES(GK1,GK2,GT,GSD1,GSD2,GSD3,GA951,GA952,GA953)	MESH 254
	CALL ANGLES(SK1,SK2,ST,SSD1,SSD2,SSD3,SA951,SA952,SA953)	MESH 255
	WRITE(LPT,133) NL ,GDEC,GINC,GK1,GK2,GAZ,GSD2,GSD1,GA952,GA951,	MESH 256
	* GT(1), GT(3), GT(6)	MESH 257
133	FORMAT('0 LINES-T PRE-TILT: ',I3,2F7.1,2F10.2,F7.1,3X,2F7.1,	MESH 258
	* 2X,2F7.1,2X,3F8.3)	MESH 259
	WRITE(LPT, 76) NL ,SDEC,SINC,SK1,SK2,SAZ,SSD2,SSD1,SA952,SA951,	MESH 260
	* ST(1), ST(3), ST(6)	MESH 261
	GLLMIN = GT(6)	MESH 262
	SLLMIN = ST(6)	MESH 263
140	CONTINUE	MESH 264

C				MESH 265
C	NOW RUN AN F-RATIO TEST TO SEE WHETHER OR NOT IT WAS LEGAL TO			MESH 266
C	COMBINE THE DATA FOR METHODS 1 AND 2.			MESH 267
C				MESH 268
	IF ((NL.LE.2).OR.(NP.LE.2)) GO TO 150			MESH 269
	WRITE(LPT,143)			MESH 270
143	FORMAT('0 TEST THE VALIDITY OF COMBINATION WITH WATSONS F-RATIO')			MESH 271
	WRITE(LPT,145)			MESH 272
145	FORMAT('0 DIRECTIONAL F-TEST: D.F. NUMERATOR D.F. DENOMINATE			MESH 273
	*TOR F-RATIO')			MESH 274
	INUM = 2			MESH 275
	IDEN = NL + NP - 4			MESH 276
	GF = (FLOAT(IDEN)/2.)*(GCLMIN - GPLMIN - GLLMIN)/(GPLMIN + GLLMIN)			MESH 277
	SF = (FLOAT(IDEN)/2.)*(SCLMIN - SPLMIN - SLLMIN)/(SPLMIN + SLLMIN)			MESH 278
	WRITE(LPT,146) INUM,IDEN,GF			MESH 279
146	FORMAT('0 PRE-TILT CORRECTION:',5X,I7,10X,I7,14X,F10.3)			MESH 280
	WRITE(LPT,147) INUM,IDEN,SF			MESH 281
147	FORMAT(' POST-TILT : ',5X,I7,10X,I7,14X,F10.3)			MESH 282
150	CONTINUE			MESH 283
C				MESH 284
C	DONE WITH THIS DATA. GO BACK FOR MORE, IF ANY			MESH 285
C				MESH 286
	GO TO 5			MESH 287
200	CONTINUE			MESH 288
	STOP			MESH 289
	END			MESH 290

SUBROUTINE SUMPRD

J.L. KIRSCHVINK, PRINCETON UNIVERSITY, MARCH, 1979

PURPOSE

CREATE THE SPHERICAL MATRIX OF THE SUMS OF SQUARES AND PRODUCTS

USAGE

CALL SUMPRD(D,FI,N,FA)

DESCRIPTION OF PARAMETERS

D - ARRAY OF DECLINATION VALUES

FI - ARRAY OF INCLINATION VALUES

N - NUMBER OF SAMPLES IN THE ARRAY

FA - THE SIX ELEMENTS OF THE MATRIX ARE RETURNED IN THIS ARRAY, IN THE PROPER ORDER FOR EIGEN.

SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED

NONE

SUBROUTINE SUMPRD(D,FI,N,FA)

DIMENSION FA(6),D(200),FI(200)

DATA RA/0.017453/

DO 230 K=1,6

FA(K) = 0.

DO 240 K = 1,N

X = COS(RA*FI(K))*COS(RA*D(K))

Y = COS(RA*FI(K))*SIN(RA*D(K))

Z = SIN(RA*FI(K))

FA(1) = FA(1) + X*X

FA(2) = FA(2) + X*Y

FA(3) = FA(3) + Y*Y

FA(4) = FA(4) + X*Z

FA(5) = FA(5) + Y*Z

FA(6) = FA(6) + Z*Z

RETURN

END

SMPRD001

SMPRD002

SMPRD003

SMPRD004

SMPRD005

SMPRD006

SMPRD007

SMPRD008

SMPRD009

SMPRD010

SMPRD011

SMPRD012

SMPRD013

SMPRD014

SMPRD015

SMPRD016

SMPRD017

SMPRD018

SMPRD019

SMPRD020

SMPRD021

SMPRD022

SMPRD023

SMPRD024

SMPRD025

SMPRD026

SMPRD027

SMPRD028

SMPRD029

SMPRD030

SMPRD031

SMPRD032

SMPRD033

SMPRD034

SMPRD035

SMPRD036

SMPRD037

C	SUBROUTINE ANGLES	ANGLE001
C	J.L. KIRSCHVINK	ANGLE002
C		ANGLE003
C	COMPUTE THE ERROR ANGLES AROUND THE EIGENVECTORS, BOTH THE	ANGLE004
C	ONE-SIGMA AND 95% CONFIDENCE. (AFTER BINGHAM, 1974)	ANGLE005
C		ANGLE006
	SUBROUTINE ANGLES(K1,K2,E,S12,S13,S23,A12,A13,A23)	ANGLE007
	DIMENSION E(6)	ANGLE008
	REAL K1,K2,K3	ANGLE009
	DATA DEG/57.29578/	ANGLE010
C	E(6),E(3), AND E(1) ARE THE EIGENVALUES FROM EIGEN	ANGLE011
	W1 = E(6)	ANGLE012
	W2 = E(3)	ANGLE013
	W3 = E(1)	ANGLE014
C	NOTE THAT K1 < K2 < K3 = 0	ANGLE015
	K3 = 0.0	ANGLE016
C	FIND THE ANGULAR STANDARD DEVIATIONS	ANGLE017
	D12 = ABS((K1-K2)*(W1-W2))	ANGLE018
	D13 = ABS((K1-K3)*(W1-W3))	ANGLE019
	D23 = ABS((K2-K3)*(W2-W3))	ANGLE020
	S12 = DEG/SQRT(2.*D12)	ANGLE021
	S13 = DEG/SQRT(2.*D13)	ANGLE022
	S23 = DEG/SQRT(2.*D23)	ANGLE023
C	FIND BINGHAM'S 95% CONFIDENCE ANGLES	ANGLE024
	CHISQ2 = 5.99	ANGLE025
	CHISQ2 = SQRT(CHISQ2)	ANGLE026
	A12 = CHISQ2 * S12	ANGLE027
	A13 = CHISQ2 * S13	ANGLE028
	A23 = CHISQ2 * S23	ANGLE029
	RETURN	ANGLE030
	END	ANGLE031

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C      SUBROUTINE BINGHM
C          ADAPTED FROM T.C. ONSTOTT, MARCH 1979
C
C      PURPOSE
C          GIVEN THE 3 EIGENVALUES FROM THE SPHERICAL MOMENT OF INERTIA
C          ANALYSIS, FIND THE TWO BINGHAM CONCENTRATION PARAMETERS.
C
C      FUNCTIONS AND SUBROUTINES REQUIRED
C
C          SUBROUTINE BINGHM(FL1,FL2,FL3,FK1,FK2)
C          EXTERNAL FUNCT
C          EXTERNAL INTGRL
C          REAL KP(2)
C          DIMENSION R(6),G(2)
C          DATA PI/3.14159/, LPT/6/
C          FL = FL1 + FL2 + FL3
C          R(1) = FL1/FL
C          R(3) = FL2/FL
C          R(6) = FL3/FL
C          KP(2) = (R(3) - R(1))/R(3)
C          KP(1) = (R(6) - R(1))/R(6)
C          IF(ABS(KP(1)).LT.25.) GO TO 201
C          KP(1) = KP(1)/2.
C          GO TO 202
C201  IF(ABS(KP(1)).GT.2.0) GO TO 202
C          KP(1) = KP(1) * 2.
C202  IF(ABS(KP(2)).LT.25.) GO TO 203
C          KP(2) = KP(2)/2.
C          GO TO 204
C203  IF(ABS(KP(2)).GT.2.0) GO TO 204
C          KP(2) = KP(2) * 2.
C204  CONTINUE
C          IF(KP(1)/KP(2).LT.2.0) GO TO 225
C          FFKP = ABS((KP(1) - KP(2))/(KP(1)+KP(2)))
C          IF(FFKP.GT.0.40.AND.FFKP.LT.0.60) GO TO 250
C2111 IF(FFKP.LT.0.40) GO TO 225
C      THIS ESTIMATE IS FOR EQUATORIAL DISTRIBUTIONS
C211  IF(ABS(KP(1)).LT.4.0.AND.FFKP.LT.0.70) GO TO 215
C          KO = 1./(2.*R(6))
C          GO TO 220
C215  KO = (15./4.) * (1. - 3.*R(6))
C220  DO = R(1) - R(3)
C          SO = R(1) + R(3)
C          DELTA = ABS(2.0 * (DO/SO) * (KO/((KO-1.5)+1.)))
C          KP(1) = -KO - DELTA
C          KP(2) = -2.0 * DELTA
C          GO TO 250
C      THIS ESTIMATE IS FOR POLAR DISTRIBUTIONS
C225  IF(ABS(KP(1)).LT.4.0.AND.FFKP.GT.0.3) GO TO 230
C          KO = 1./(1. - R(1))
C          GO TO 235
C230  KO = (15./4.) * (1.-3.*R(1))
C235  DO = R(3) - R(6)
C          SO = R(3) + R(6)
C          DELTA = ABS(2.0 * (DO/SO) * (KO/((KO-1.5)+1.)))
C          KP(1) = -KO - DELTA
C          KP(2) = -KO + DELTA
C250  EST = 1./(-ALOG(ABS(12.*PI*R(6))) + KP(1)*R(6) + KP(2)*R(3))
C          LIMIT = 20

```

BINGH001
 BINGH002
 BINGH003
 BINGH004
 BINGH005
 BINGH006
 BINGH007
 BINGH008
 BINGH009
 BINGH010
 BINGH011
 BINGH012
 BINGH013
 BINGH014
 BINGH015
 BINGH016
 BINGH017
 BINGH018
 BINGH019
 BINGH020
 BINGH021
 BINGH022
 BINGH023
 BINGH024
 BINGH025
 BINGH026
 BINGH027
 BINGH028
 BINGH029
 BINGH030
 BINGH031
 BINGH032
 BINGH033
 BINGH034
 BINGH035
 BINGH036
 BINGH037
 BINGH038
 BINGH039
 BINGH040
 BINGH041
 BINGH042
 BINGH043
 BINGH044
 BINGH045
 BINGH046
 BINGH047
 BINGH048
 BINGH049
 BINGH050
 BINGH051
 BINGH052
 BINGH053
 BINGH054
 BINGH055
 BINGH056
 BINGH057
 BINGH058
 BINGH059
 BINGH060

```
EPS = 0.005
N = 2
CALL FMFP(FUNCT,N,R(3),R(6),KP,F,G,EST,EPS,LIMIT,IER,H)
IF(IER.NE.3) WRITE(LPT,260)
260  FORMAT(' **** WARNING ****  FMFP DID NOT CONVERGE ****')
      FK1 = KP(1)
      FK2 = KP(2)
      RETURN
      END
```

```
BINGH061
BINGH062
BINGH063
BINGH064
BINGH065
BINGH066
BINGH067
BINGH068
BINGH069
```

C	SUBROUTINE FDOT	FDOT 001
C	J.L. KIRSCHVINK, MARCH 1979	FDOT 002
C		FDOT 003
C	PURPOSE	FDOT 004
C	MAKE THE LEAST-SQUARES DIRECTION PARALLEL TO THE THE FISHER	FDOT 005
C	DIRECTION. THE DIRECTION OF DEC AND FINC ARE REVERSED IF	FDOT 006
C	THEY ARE GENERALLY ANTIPARALLEL.	FDOT 007
C	SUBROUTINES NEEDED	FDOT 008
C	DOT	FDOT 009
C		FDOT 010
	SUBROUTINE FDOT(FDEC,FINC,DEC,INC)	FDOT 011
	REAL INC	FDOT 012
	DATA RA/.017453/	FDOT 013
	DIMENSION E(6)	FDOT 014
	E(1) = COS(FDEC*RA) * COS(FINC*RA)	FDOT 015
	E(2) = SIN(FDEC*RA) * COS(FINC*RA)	FDOT 016
	E(3) = SIN(FINC*RA)	FDOT 017
	E(4) = COS(DEC*RA) * COS(INC*RA)	FDOT 018
	E(5) = SIN(DEC*RA) * COS(INC*RA)	FDOT 019
	E(6) = SIN(INC*RA)	FDOT 020
	TEST = DOT(E(1),E(4))	FDOT 021
	IF(TEST) 10,10,20	FDOT 022
10	INC = -INC	FDOT 023
	DEC = DEC + 180.	FDOT 024
20	IF(DEC.LT.0.) DEC = DEC + 360.	FDOT 025
	IF(DEC.GT.360.) DEC = DEC - 360.	FDOT 026
	RETURN	FDOT 027
	END	FDOT 028

	SUBROUTINE FISHER(D,FI,N,R,FK,ALPHA,CSD,DEC,FINC)	FISH 001
	DATA RA/.317453/,LPT/6/,IN/5/, DEG/57.29578/	FISH 002
	DIMENSION D(100), FI(100)	FISH 003
	X=0.	FISH 004
	Y=0.	FISH 005
	Z=0.	FISH 006
	DO 30 K=1,N	FISH 007
	IF(D(K).LT.0.) D(K) = D(K) + 360.	FISH 008
	Y1 = COS(FI(K)*RA) * SIN(D(K)*RA)	FISH 009
	X1 = COS(FI(K)*RA)*COS(D(K)*RA)	FISH 010
	Z1 = SIN(FI(K)*RA)	FISH 011
	IF(X*X1+Y*Y1+Z*Z1) 22,25,25	FISH 012
22	X1=-X1	FISH 013
	Y1=-Y1	FISH 014
	Z1=-Z1	FISH 015
25	X=X+X1	FISH 016
	Y=Y+Y1	FISH 017
	Z=Z+Z1	FISH 018
30	CONTINUE	FISH 019
	CALL POLAR(X,Y,Z,DEC,FINC,R)	FISH 020
	FK = FLOAT(N-1)/(FLOAT(N) - R)	FISH 021
	ALPHA = ARCOS(1.-((FLOAT(N)-R)/R)*(20.**((1./FLOAT(N-1))-1.)))	FISH 022
	@ * DEG	FISH 023
	IF(FK- 100.) 34, 35, 35	FISH 024
34	THETA = ARCOS((1/FK) * ALOG(EXP(FK) - 0.95*(EXP(FK) - EXP(-FK))))	FISH 025
	@ * DEG	FISH 026
	CSD = ARCOS((1./FK) * ALOG(EXP(FK) - 0.63*(EXP(FK) - EXP(-FK))))	FISH 027
	@ * DEG	FISH 028
	GO TO 36	FISH 029
35	THETA = 140./SQRT(FK)	FISH 030
	CSD = 81./SQRT(FK)	FISH 031
36	CONTINUE	FISH 032
	RETURN	FISH 033
	END	FISH 034

245
255

	DATA RA/.017453/,LPT/6/,IN/5/, DEC/57.29573/	MAIN 270
	DATA TEST/' '	MAIN 275
	DIMENSION COMM(2)	MAIN 280
	DIMENSION A(20),X1(200),Y1(200), Z1(200),X2(74),Y2(74),Z2(74)	MAIN 285
	DIMENSION T(2),E(2)	MAIN 290
	READ(IN,1,END=200) FN	MAIN 295
1	FORMAT(F10.2)	MAIN 300
	N=INT(FN) + 1	MAIN 305
C		MAIN 310
C	SET UP THE PLOTTING FILE	MAIN 315
C		MAIN 320
	CALL NGRAPH(N*1200+500,300,50,'INDIAINK','BLACK ','ALLWHITE',1)	MAIN 325
5	READ(IN,10,END=200) A	MAIN 330
10	FORMAT(20A4)	MAIN 335
	CALL PLOT(5.,4.,-3)	MAIN 340
C	PUT TICKS ON THE CIRCLE	MAIN 345
	CALL SYMBOL(0.,0.,0.15,3,90.,-1)	MAIN 350
	CALL SYMBOL(-4.,0.,0.15,13,90.,-1)	MAIN 355
	CALL SYMBOL(0.,4.,0.15,13, 0.,-1)	MAIN 360
	CALL SYMBOL(4.,0.,0.15,13,90.,-1)	MAIN 365
	CALL SYMBOL(0.,-4.,0.15,13, 0.,-1)	MAIN 370
C		MAIN 375
C	DRAW THE CIRCLE	MAIN 380
C		MAIN 385
	CALL PLOT(0.,-4.,3)	MAIN 390
	DO 20 I=1,125	MAIN 395
	PI=3.141592653589793	MAIN 400
	Y=-4.*COS(PI*PA)	MAIN 405
	X= 4.*SIN(PI*PA)	MAIN 410
20	CALL PLOT(X,Y,2)	MAIN 415
C		MAIN 420
C	NOW PLOT THE DATA	MAIN 425
C		MAIN 430
25	READ(IN,27,END=200) SAMP, DEC, FINC, ALAT, ALONG, AMIN, AMAX,	MAIN 435
	* AZIM, COMM	MAIN 440
27	FORMAT(A4,1X,7F3.2,2A4)	MAIN 445
	IF(SAMP.EQ.TEST) GO TO 100	MAIN 450
	WRITE(LPT,28) SAMP,DEC,FINC,AMIN,AMAX,AZIM,COMM	MAIN 455
28	FORMAT('0 ',A4,5X,2F10.2,20X,3F10.2,2A4)	MAIN 460
	CALL EVAXIS(AZIM, DEC, FINC, E)	MAIN 465
	CALL CONF(AMAX, AMIN, E, Y2, Y2, Z2)	MAIN 470
C		MAIN 475
C	PLOT THE CONE OF CONFIDENCE	MAIN 480
C		MAIN 485
	DO 40 I = 1,74	MAIN 490
	X = X2(I)	MAIN 495
	Y = Y2(I)	MAIN 500
	Z = Z2(I)	MAIN 505
	CALL POLAR(X,Y,Z,DEC,FINC,FINT)	MAIN 510
	RAD=SIN((1.5708-ABS(FINC)*RA)/(2.))*SQRT(2.)*4.	MAIN 515
	X=-RAD*COS(DEC*RA)	MAIN 520
	Y=RAD*SIN(DEC*RA)	MAIN 525
	IF(I.EQ.74) GO TO 110	MAIN 530
	IF(I.EQ.1) CALL PLOT(X,Y,3)	MAIN 535
40	CALL PLOT(X,Y,2)	MAIN 540
110	CONTINUE	MAIN 545

C		MAIN 550
C	NOW PLOT AN APPROPRIATE SYMBOL IN THE CENTER	MAIN 555
C		MAIN 560
	IF(FINC) 125,125,120	MAIN 565
120	CALL SYMBOL(X,Y,0.04,0,0.,-1)	MAIN 570
	CALL SYMBOL(X,Y,0.07,0,0.,-1)	MAIN 575
	CALL SYMBOL(X,Y,0.10,0,0.,-1)	MAIN 580
125	CALL SYMBOL(X,Y,0.13,0,0.,-1)	MAIN 585
	GO TO 25	MAIN 590
100	CONTINUE	MAIN 595
	CALL SYMBOL(4.5,-.2,0.125,'130',90.,3)	MAIN 600
	CALL SYMBOL(5.,-4.,0.125,A,90.,30)	MAIN 605
	CALL PLOT(7.,-4.0,-3)	MAIN 610
C		MAIN 615
C	FINISHED WITH THIS ONE - GO GET THE NEXT	MAIN 620
C		MAIN 625
	WRITE(LPT,10) A	MAIN 630
	GO TO 5	MAIN 635
200	CONTINUE	MAIN 640
	CALL ENDPLT	MAIN 645
	STOP	MAIN 650
	END	MAIN 655

SUBROUTINE EVAXIS

J.L. KIRSCHVINK, PRINCETON UNIVERSITY, SEPT. 1978

PURPOSE

THIS PROGRAM FINDS THE ORIGINAL INERTIAL AXES WHICH WERE GENERATED IN THE MOMENT OF INERTIA CALCULATION FOR THE BINGHAM STATISTICS. THE INERTIAL AXES ARE THE EIGENVECTORS OF THE MATRIX OF SUMS OF SQUARES AND PRODUCTS, AND MAY BE RE-CALCULATED FROM THE REMANENCE DIRECTION AND THE ORIENTATION AZIMUTH. THE EIGENVECTOR MATRIX E(9) IS THE ROTATION MATRIX USED IN SUBROUTINE CONE.

USAGE

CALL EVAXIS(AZIM, DEC, FINC, E)

DESCRIPTION OF PARAMETERS

AZIM - THE DESIRED ORIENTATION AZIMUTH OF THE ERROR ELLIPSE.
 DEC - THE DECLINATION OF THE REMANENCE DIRECTION.
 FINC - THE INCLINATION OF THE REMANENCE DIRECTION
 E - (1X9) MATRIX OF EIGENVECTORS FROM THE ORIGINAL MOMENT-OF-INERTIA ANALYSIS. (COMPUTED HERE)

SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED
VTPOL, UCROSS

SUBROUTINE EVAXIS(AZIM, DEC, FINC, E)

DIMENSION E(9)

DATA RA /0.017453/, DEG /57.29578/

THE 3RD EIGENVECTOR, (E(7), E(8), E(9)), IS THE REMANENCE DIRECTION.

E(7) = COS(FINC*RA)*COS(DEC*RA)

E(8) = COS(FINC*RA)*SIN(DEC*RA)

E(9) = SIN(FINC*RA)

THE 2ND EIGENVECTOR IS 90 DEGREES AWAY FROM THE FIRST, IN THE DIRECTION OF THE ORIENTATION AZIMUTH. IT MAY BE FOUND BY COMPUTING A VGP POSITION AT THE EV3 SITE, WITH THE DEC=OR.AZ., AND THE INC = 0.0.

PLUNG = 0.0

CALL VTPOL(DEC, FINC, AZIM, PLUNG, VGPINC, VGPDEC)

E(4) = COS(VGPINC*RA)*COS(VGPDEC*RA)

E(5) = COS(VGPINC*RA)*SIN(VGPDEC*RA)

E(6) = SIN(VGPINC*RA)

THE FIRST EIGENVECTOR IS THE UNIT CROSS PRODUCT OF THE OTHERS.

CALL UCROSS(E(1), E(4), E(7))

RETURN

END

EVAX0010
 EVAX0020
 EVAX0030
 EVAX0040
 EVAX0050
 EVAX0060
 EVAX0070
 EVAX0080
 EVAX0090
 EVAX0100
 EVAX0110
 EVAX0120
 EVAX0130
 EVAX0140
 EVAX0150
 EVAX0160
 EVAX0170
 EVAX0180
 EVAX0190
 EVAX0200
 EVAX0210
 EVAX0220
 EVAX0230
 EVAX0240
 EVAX0250
 EVAX0260
 EVAX0270
 EVAX0280
 EVAX0290
 EVAX0300
 EVAX0310
 EVAX0320
 EVAX0330
 EVAX0340
 EVAX0350
 EVAX0360
 EVAX0370
 EVAX0380
 EVAX0390
 EVAX0400
 EVAX0410
 EVAX0420
 EVAX0430
 EVAX0440
 EVAX0450
 EVAX0460
 EVAX0470
 EVAX0480
 EVAX0490
 EVAX0500
 EVAX0510

SUBROUTINE CONE

J.L. KIRSCHVINK, PRINCETON UNIVERSITY, JUNE, 1973

PURPOSE

THIS ROUTINE GENERATES THE 95% CONE OF CONFIDENCE ABOUT
A REMANENCE DIRECTION, GIVEN THE ERROR ANGLES AND THE
EIGENVECTOR MATRIX.

USAGE

CALL CONE(AMAX,AMIN,E,X,Y,Z)

DESCRIPTION OF PARAMETERS

AMAX - LARGEST HALF-ANGLE (DECIMAL DEGREES) OF 95% CONFIDENCE

AMIN - SMALLEST HALF-ANGLE

E - 9 BY 1 ARRAY CONTAINING THE ASSOCIATED EIGENVECTORS
(E(4),E(5),E(6)) IS THE DIRECTION OF AMAX, AND THE
REMANENCE DIRECTION ABOUT WHICH THE CONE IS MADE IS
(E(7),E(8),E(9))

X,Y,Z - 74 BY 1 ARRAY CONTAINING THE POINTS CALCULATED
FOR THE 95% CONE OF CONFIDENCE. 73 POINTS ARE ON THE
CONE, AND THE LAST GIVES THE POSITION OF THE CENTER.

SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED

NONE

METHOD

THE POINTS ON THE ERROR ELLIPSE ARE FIRST GENERATED IN
THE INERTIAL FRAME, AND ROTATED BACK TO THE GEOGRAPHIC OR
STRATIGRAPHIC SYSTEM.

WARNING

DO NOT TRY TO PLOT POLES WITH ERRORS OF GREATER THAN 180.

SUBROUTINE CONE(AMAX, AMIN, E, X, Y, Z)

DIMENSION X(74), Y(74), Z(74), E(9)

RAD = 0.017453

GENERATE THE 73 POINT ARRAY IN INERTIAL COORDINATES

DO 10 I = 1,73

PHI = FLOAT(5*I)*RAD

A = SIN(AMIN*RAD)

B = SIN(AMAX*RAD)

R = 1./SQRT(SIN(PHI)*SIN(PHI)/(A*A) + COS(PHI)*COS(PHI)/(B*B))

Y(I) = R*COS(PHI)

X(I) = -R*SIN(PHI)

Z(I) = SQRT(1.-P*P)

CONE0010

CONE0020

CONE0030

CONE0040

CONE0050

CONE0060

CONE0070

CONE0080

CONE0090

CONE0100

CONE0110

CONE0120

CONE0130

CONE0140

CONE0150

CONE0160

CONE0170

CONE0180

CONE0190

CONE0200

CONE0210

CONE0220

CONE0230

CONE0240

CONE0250

CONE0260

CONE0270

CONE0280

CONE0290

CONE0300

CONE0310

CONE0320

CONE0330

CONE0340

CONE0350

CONE0360

CONE0370

CONE0380

CONE0390

CONE0400

CONE0410

CONE0420

CONE0430

CONE0440

CONE0450

CONE0460

CONE0470

```

C
C NOW X, Y, AND Z MUST BE ROTATED FROM INERTIAL COORDINATES BACK
C INTO GEOGRAPHIC OR STRATIGRAPHIC COORDINATES.
    DO 20 I = 1, 73
      X1 = X(I)
      Y1 = Y(I)
      Z1 = Z(I)
      X(I) = E(1)*X1 + E(4)*Y1 + E(7)*Z1
      Y(I) = E(2)*X1 + E(5)*Y1 + E(8)*Z1
      Z(I) = E(3)*X1 + E(6)*Y1 + E(9)*Z1
20
C
C THE 74TH POINT STORES THE DIRECTION AROUND WHICH THE ERROR CONE
C IS CONSTRUCTED.
C
      X(74) = E(7)
      Y(74) = E(8)
      Z(74) = E(9)
      RETURN
      END

```

```

CONE0480
CONE0490
CONE0500
CONE0510
CONE0520
CONE0530
CONE0540
CONE0550
CONE0560
CONE0570
CONE0580
CONE0590
CONE0600
CONE0610
CONE0620
CONE0630
CONE0640
CONE0650
CONE0660

```

```

SUBROUTINE VTPOL ( DLONG, DLAT, DECLP, INCLP, PLAT, PLONG)
REAL INCLP, INCLR
DATA DEG /57.29578/, RAD /0.017453/

```

VTPOL
VTPOL010
VTPOL015
VTPOL020
VTPOL025
VTPOL030
VTPOL035
VTPOL040
VTPOL045
VTPOL050
VTPOL055
VTPOL060
VTPOL065
VTPOL070
VTPOL075
VTPOL080
VTPOL085
VTPOL090
VTPOL095
VTPOL100
VTPOL105
VTPOL110
VTPOL115
VTPOL120
VTPOL125
VTPOL130
VTPOL135
VTPOL140
VTPOL145
VTPOL150
VTPOL155
VTPOL160
VTPOL165
VTPOL170
VTPOL175
VTPOL180
VTPOL185
VTPOL190
VTPOL195
VTPOL200
VTPOL205
VTPOL210
VTPOL215
VTPOL220
VTPOL225
VTPOL230
VTPOL235
VTPOL240
VTPOL245
VTPOL250
VTPOL255
VTPOL
VTPOL265
VTPOL270
VTPOL275
VTPOL280

```

C THE PALEOMAGNETIC POLE LATITUDE AND LONGITUDE ARE NOW CALCULATED
C USING THE DECLINATION AND INCLINATION OF THE SPECIMEN AND THE LATITUDE
C AND LONGITUDE OF THE SAMPLING SITE.

```

```

IF(DLONG.LT.0.0) DLONG = 360. + DLONG

```

```

SLATR=DLAT*PAD

```

```

SLONR=DLONG*PAD

```

```

DECLR = DECLP * RAD

```

```

INCLR = INCLP * RAD

```

```

P=0.

```

```

IF(ABS(INCLP) - 90.0) 146,155,146

```

```

SIGN=1.

```

```

IF (INCLP) 147,148,148

```

```

SIGN=-1.0

```

```

P=(3.14159/2.) *SIGN

```

```

IF (INCLP) 149,155,149

```

```

IF(COS(INCLR).EQ.0.0) TANIN=SIN(INCLR)*1.000E 38

```

```

IF(COS(INCLP).EQ.0.0) GO TO 500

```

```

TANIN=SIN(INCLR)/COS(INCLR)

```

```

CONTINUE

```

```

P=ATAN(2./TANIN)

```

```

IF(P) 150,155,155

```

```

P=P+3.14159

```

```

COSSL=COS(SLATR)

```

```

SX=COSSL*COS(SLONR)

```

```

SY=COSSL*SIN(SLONR)

```

```

SZ=SIN(SLATR)

```

```

COSSA=SZ

```

```

SA=ARCOS(COSSA)

```

```

COSP=COS(P)

```

```

SINSA=SIN(SA)

```

```

COSZ=COSP*COSSA+SIN(P)*SINSA*COS(DECLR)

```

```

Z=ARCOS(COSZ)

```

```

PLATR=1.57080-Z

```

```

PZ=SIN(PLATR)

```

```

PLAT=PLATR*DEG

```

```

COSB=(COSP-(COSZ*COSSA))/(SIN(Z)*SINSA)

```

```

IF(DECLP - 180.0) 165,165,160

```

```

150 PLONG=SLONR-ARCOS(COSB)

```

```

GO TO 170

```

```

165 PLONG=SLONR+ARCOS(COSB)

```

```

170 CONTINUE

```

```

COSPL=COS(PLAT)

```

```

PY=COSPL*SIN(PLONG)

```

```

COSPG=COS(PLONG)

```

```

PLONG=ARCOS(COSPG)*DEG

```

```

IF(PY) 175,176,176

```

```

175 PLONG=-PLONG

```

```

176 CONTINUE

```

```

180 CONTINUE

```

```

IF(PLONG.LT.0.0) PLONG = 360. + PLONG

```

```

RETURN

```

```

END

```

THE ROLE OF BIOGENIC MINERALS IN THE MAGNETIZATION OF SEDIMENTS

J.L. Kirschvink (Geological and Geophysical Sciences, Princeton University, Princeton, N.J. 08544)

H.A. Lowenstam (Div. of Geological and Planetary Sciences, California Institute of Technology, Pasadena, California 91125)

Biologic activity may be responsible for some of the single domain magnetite found in limestones, black shales, coal, peat, and other freshwater and marine sediments.

Four groups of organisms are known to biologically synthesize magnetite: (1) mud bacteria, (2) molluscs (chitons), (3) Arthropods, and (4) vertebrates (birds). The birds and Arthropods occasionally produce fine-grained (SD or SPM) magnetite which appears to be used to sense the direction of the local magnetic field. The amount of magnetite used is small, and not likely to be geologically important. We have found fresh embryonic sharks to be magnetic ($\sim 10^{-6}$ emu/g), but have not yet conclusively identified the material responsible. Chitons precipitate magnetite crystals (.03-.20 μ m) in their major lateral teeth, and as a group shed $\sim 5.4 \times 10^9$ gr annually into all oceanic sediments; mainly in tropical waters. The crystals seem to be protected from oxidation during transport and burial by an organic matrix. Magnetite in Chitons is always formed by the biochemical conversion of Ferrihydrite.

Magnetotactic bacteria are potentially the most important source of SD organic magnetite. These bacteria are found both in marine and fresh water sediments, and synthesize regular sub-micron crystals which are released into the environment after death. Population densities in some reducing sediments are high enough to significantly contribute to their remanent magnetism ($\sim 2-12 \times 10^{-9}$ g/ml). The presence of such bacteria would account for positive correlations between the organic carbon content of sediment and the remanent magnetism, as has been seen in Lake Windermere and elsewhere.

